NOAA TECHNICAL MEMORANDUM NWS CR-99

# CENTRAL REGION APPLIED RESEARCH PAPERS
# 99-1 THROUGH 99-7

National Weather Service Central Region
Scientific Services Division
Kansas City, Missouri

NOVEMBER 1989

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

## NOAA TECHNICAL MEMORANDA
### National Weather Service, Central Region Subseries

The National Weather Service Central Region (CR) subseries provides an informal medium for the documentation and quick dissemination of results not appropriate, or not yet ready, for formal publication. The series is used to report on work in progress, to describe technical procedures and practices, or to relate progress to a limited audience. These Technical Memoranda report on investigations devoted primarily to regional and local problems of interest mainly to regional personnel, and hence will not be widely distributed.

Papers 1 through 15 are in the former series, ESSA Technical Memoranda, Central Region Technical Memoranda (CRTM); Papers 16 through 36 are in the former series, ESSA Technical Memoranda, Weather Bureau Technical Memoranda (WBTM). Beginning with Paper 37, the papers are part of the series, NOAA Technical Memoranda NWS.

Papers that have a PB or COM number are available from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22151. Order by accession number shown in parenthesis at the end of each entry. Prices vary for all paper copies. Microfiche are $4.50. All other papers are available from the National Weather Service Central Region, Scientific Services, Room 1836, 601 East 12th Street, Kansas City, MO 64106.

### ESSA Technical Memoranda

CRTM 1 Precipitation Probability Forecast Verification Summary Nov. 1965 - Mar. 1966. SSD Staff, WBCRH, May 1966.
CRTM 2 A Study of Summer Showers Over the Colorado Mountains. William G. Sullivan, Jr., and James O. Severson, June 1966.
CRTM 3 Areal Shower Distribution - Mountain Versus Valley Coverage. William G. Sullivan, Jr., and James O. Severson, June 1966.
CRTM 4 Heavy Rains in Colorado June 16 and 17, 1965. SSD Staff, WBCRH, July 1966.
CRTM 5 The Plum Fire. William G. Sullivan, Jr., August 1966.
CRTM 6 Precipitation Probability Forecast Verification Summary Nov. 1965 - July 1966. SSD Staff, WBCRH, September 1966.
CRTM 7 Effect of Diurnal Weather Variations on Soybean Harvest Efficiency. Leonard F. Hand, October 1966.
CRTM 8 Climatic Frequency of Precipitation at Central Region Stations. SSD Staff, WBCRH, November 1966.
CRTM 9 Heavy Snow or Glazing. Harry W. Waldheuser, December 1966.
CRTM 10 Detection of a Weak Front by WSR-57 Radar. G. W. Polensky, December 1966.
CRTM 11 Public Probability Forecasts. SSD Staff, WBCRH, January 1967.
CRTM 12 Heavy Snow Forecasting in the Central United States (an Interim Report). SSD Staff, January 1967.
CRTM 13 Diurnal Surface Geostrophic Wind Variations Over the Great Plains. Wayne E. Sangster, March 1967.
CRTM 14 Forecasting Probability of Summertime Precipitation at Denver. Wm. G. Sullivan, Jr., and James O. Severson, March 1967.
CRTM 15 Improving Precipitation Probability Forecasts Using the Central Region Verification Printout. Lawrence A. Hughes, May 1967.
WBTM CR 16 Small-Scale Circulations Associated with Radiational Cooling. Jack R. Cooley, June 1967.
WBTM CR 17 Probability Verification Results (6-month and 18-month). Lawrence A. Hughes, June 1967.
WBTM CR 18 On the Use and Misuse of the Brier Verification Score. Lawrence A. Hughes, August 1967 (PB 175 771).
WBTM CR 19 Probability Verification Results (24 months). Lawrence A. Hughes, February 1968.
WBTM CR 20 Radar Prediction of the Topeka Tornado. Norman E. Prosser, April 1968.
WBTM CR 21 Wind Waves on the Great Lakes. Lawrence A. Hughes, May 1968.
WBTM CR 22 Seasonal Aspects of Probability Forecasts: 1. Summer. Lawrence A. Hughes, June 1968 (PB 185 733).
WBTM CR 23 Seasonal Aspects of Probability Forecasts: 2. Fall. Lawrence A. Hughes, September 1968 (PB 185 734).
WBTM CR 24 The Importance of Areal Coverage in Precipitation Probability Forecasting. John T. Curran and Lawrence A. Hughes, September 1968.
WBTM CR 25 Meteorological Conditions as Related to Air Pollution, Chicago, Illinois, April 12-13, 1963. Charles H. Swan, October 1968.
WBTM CR 26 Seasonal Aspects of Probability Forecasts: 3. Winter. Lawrence A. Hughes, December 1968 (PB 185 735).
WBTM CR 27 Seasonal Aspects of Probability Forecasts: 4. Spring. Lawrence A. Hughes, February 1969 (PB 185 736).
WBTM CR 28 Minimum Temperature Forecasting During Possible Frost Periods at Agricultural Weather Stations in Western Michigan. Marshall E. Soderberg, March 1969.
WBTM CR 29 An Aid for Tornado Warnings. Harry W. Waldheuser and Lawrence A. Hughes, April 1969.
WBTM CR 30 An Aid in Forecasting Significant Lake Snows. H. J. Rothrock, November 1969.
WBTM CR 31 A Forecast Aid for Boulder Winds. Wayne E. Sangster, February 1970.
WBTM CR 32 An Objective Method for Estimating the Probability of Severe Thunderstorms. Clarence L. David, February 1970.
WBTM CR 33 Kentucky Air-Soil Temperature Climatology. Clyde B. Lee, February 1970.
WBTM CR 34 Effective Use of Non-Structural Methods in Water Management. Verne Alexander, March 1970.
WBTM CR 35 A Note on the Categorical Verification of Probability Forecasts. Lawrence A. Hughes and Wayne E. Sangster, August 1970.
WBTM CR 36 A Comparison of Observed and Calculated Urban Mixing Depths. Donald E. Wuerch, August 1970.

### NOAA Technical Memoranda NWS

NWS CR 37 Forecasting Maximum and Minimum Surface Temperatures at Topeka, Kansas, Using Guidance from the PE Numerical Prediction Model (FOUS). Morris S. Webb, Jr., November 1970 (COM 71 00118).
NWS CR 38 Snow Forecasting for Southeastern Wisconsin. Rheinhart W. Harms, November 1970 (COM 71-00019).
NWS CR 39 A Synoptic Climatology of Blizzards on the North-Central Plains of the United States. Robert E. Black, February 1971 (COM 71-00369).
NWS CR 40 Forecasting the Spring 1969 Midwest Snowmelt Floods. Herman F. Mondschein, February 1971 (COM 71-00489).
NWS CR 41 The Temperature Cycle of Lake Michigan 1. (Spring and Summer). Lawrence A. Hughes, April 1971 (COM 71-00545).
NWS CR 42 Dust Devil Meteorology. Jack R. Cooley, May 1971 (COM 71-00628).
NWS CR 43 Summer Shower Probability in Colorado as Related to Altitude. Alois G. Topil, May 1971 (COM 71-00712).
NWS CR 44 An Investigation of the Resultant Transport Wind Within the Urban Complex. Donald E. Wuerch, June 1971 (COM 71-00766).
NWS CR 45 The Relationship of Some Cirrus Formations to Severe Local Storms. William E. Williams, July 1971 (COM 71-00844).
NWS CR 46 The Temperature Cycle of Lake Michigan 2. (Fall and Winter). Lawrence A. Hughes, September 1971 (COM 71-01039).
NWS CR 47 Practical Application of a Graphical Method of Geostrophic Wind Determination. C.B. Johnson, November 1971 (COM 71-01084).
NWS CR 48 Manual of Great Lakes Ice Forecasting. C. Robert Snider, December 1971 (COM 72-10143).

(Continued on Back Inside Cover)

NOAA TECHNICAL MEMORANDUM NWS CR-99



# CENTRAL REGION APPLIED RESEARCH PAPERS
# 99-1 THROUGH 99-7

National Weather Service Central Region
Scientific Services Division
Kansas City, Missouri

November 1989

UNITED STATES DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Weather Service

Robert A. Mosbacher, Secretary

John A. Knauss, Under Secretary

Elbert W. Friday, Jr., Assistant Administrator

CENTRAL REGION APPLIED RESEARCH PAPERS

TABLE OF CONTENTS

# CENTRAL REGION APPLIED RESEARCH PAPER 99-1

## DECEMBER 14-15, 1987 SNOW STORM POST-ANALYSIS

Charles H. Myers
National Weather Service Forecast Office
Des Moines, Iowa

### 1. Introduction

The December 14-15, 1987 snow storm which occurred across the upper Midwest was one of the most intense winter weather systems to impact this area during the past ten years. One problem that plagues all forecasters when dealing with a rapidly developing system is the discontinuities which seem to occur between different computer models and different model runs. This post-analysis of the December 14-15 storm attempts to highlight this problem by concentrating on four main forecast features. They are: (1) the movement of the 500 mb low, (2) the movement of the surface low track, (3) the thickness fields, (4) the evolution of the snow area evolution, and (5) the "MAGIC CHART."

### 2. Analysis

Figure 1 depicts the 24, 36, and 48 hour forecast of the LFM, NGM, and SPM 500 mb low track from the 13/12Z run. First appearances indicated that the NGM and SPM were nearly identical on the track of the storm with the LFM distinctly south and lacking a recurvature point. In fact, the LFM had an open trough until 48 hours, which would account for its more southerly track. Heights by the NGM were too low at 24 and 36 hours but very close at 48. The LFM and SPM were very similar on heights with all models deepening the low at 48 hours. Could this deepening have accounted for the NGM/SPM 48 hour forecast positioning the system west of what was observed? The 36 hour recurvature point was forecast exceptionally well by both the NGM and SPM.

Figure 2 shows the next run dated 14/00Z. Once again the LFM was farther south with the NGM acting more as a compromise forecast between the LFM and SPM, at least through 36 hours. Note on this run that the LFM trended more towards the previous NGM/SPM solution, including a recurvature point and closed lows. The trend of strong deepening over Iowa continued. Curiously, the NGM at 24 hours was nearer to the previous run's LFM track, trending well south of observed before pulling back north at 48 hours. The most consistent model from the previous run was the SPM.

Figure 3 depicts the 14/12Z run. Locations of the 500 mb low from initial time through 36 hours show this run was similar to the previous run in that the NGM acted as a somewhat compromise forecast between the SPM and

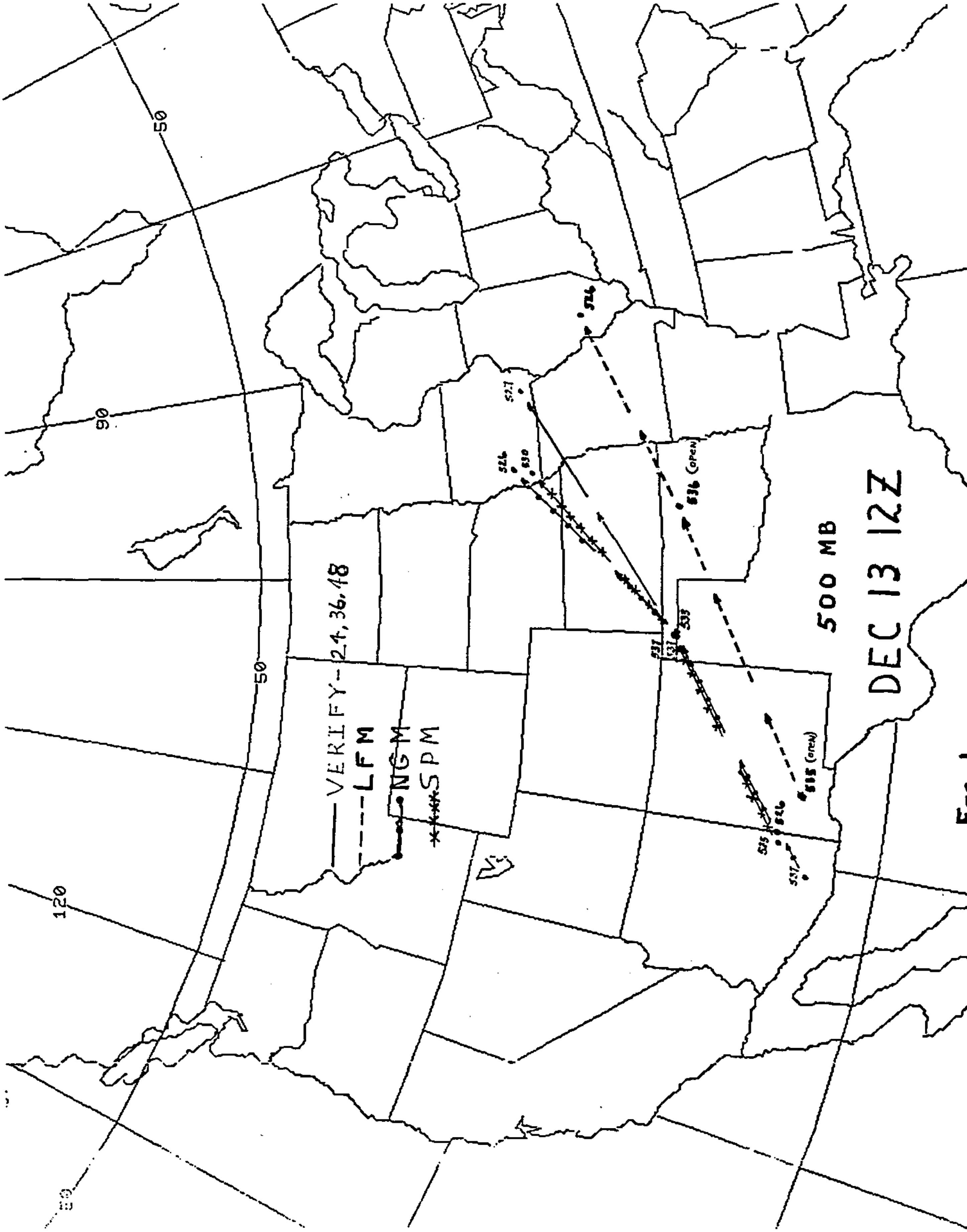



FIG 1

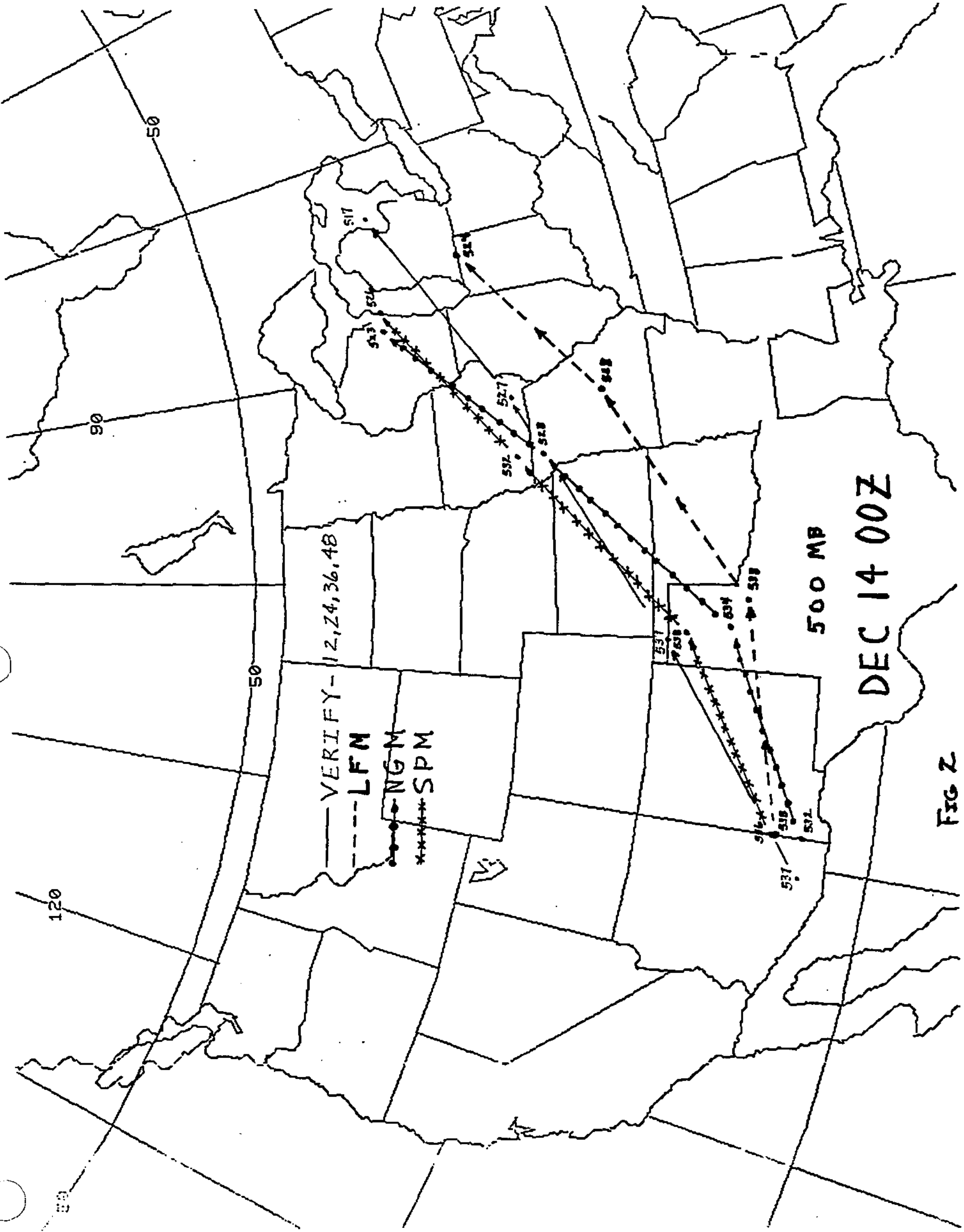



FIG 2

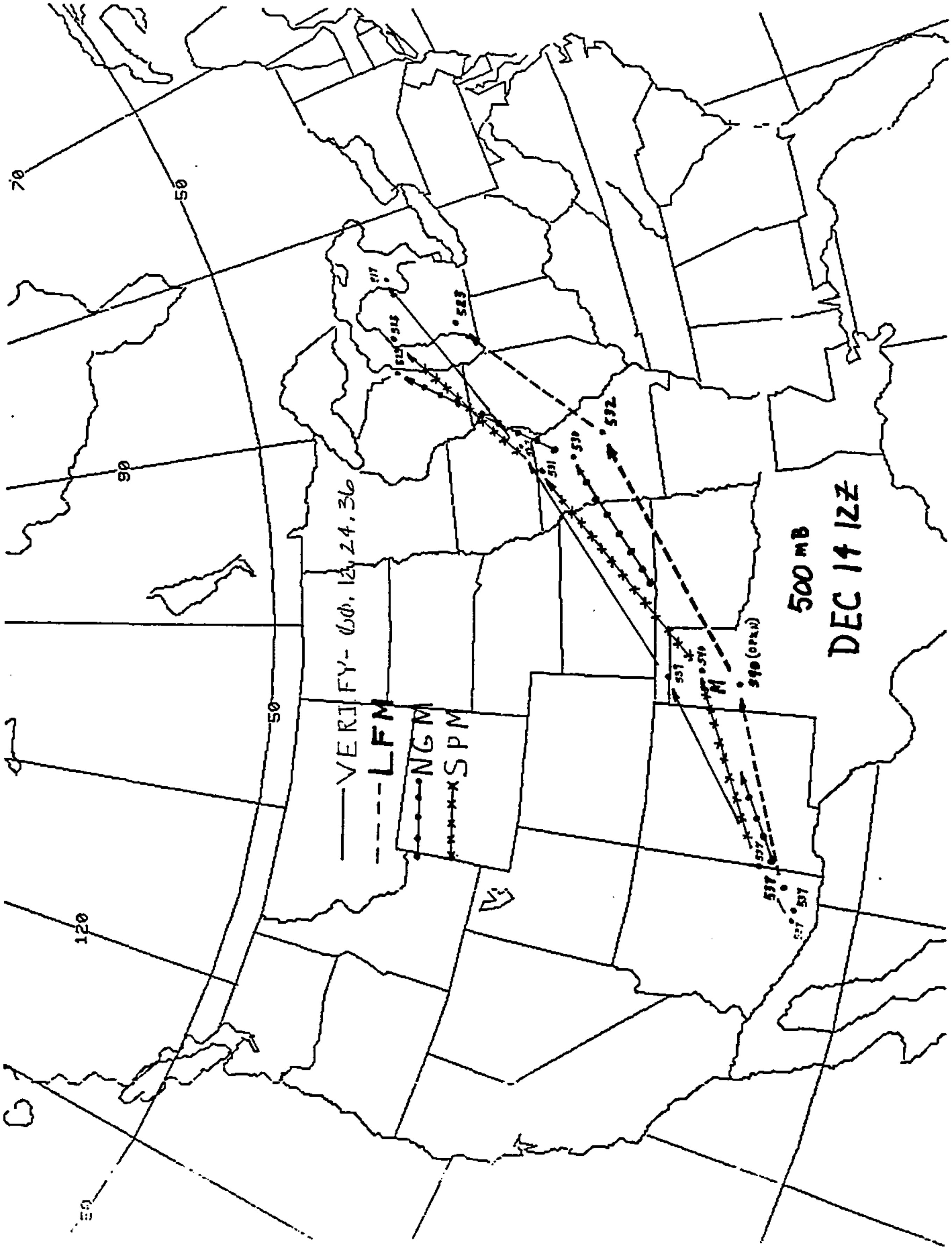



FIG 3

LFM. Again, the LFM was farther south, with a nearly identical track to the previous run. An eastward adjustment occurred to the NGM and SPM tracks through 24 hours with a 36 hour forecast which was similar to the previous 48 hour forecast. Once again the NGM was south of observed track with a northward cross-over between 24 and 36 hours. At 36 hours, the models were still not deep enough. The SPM remained the most consistent model.

3. Surface Low

Figure 4 displays the 13/12Z 24, 36, and 48 hour forecast and verification tracks. The main push of the surface low was across Texas, to near Arkansas then to the northeast. The 24 hour LFM/NGM tracks were quite similar until 36 hours when they begin to diverge. Note the lack of deepening by the NGM at 48 hours as compared to the LFM. The SPM forecast kept the system to the south through 24 hours, then a compromise track was established compared to the other two. The SPM also lacked deepening by 48 hours. The general recurvature of all models was in or near Arkansas. Since the position of the surface low greatly affects the location of the heavy snow band in Iowa, one would probably hesitate on issuing a watch using this forecast. In the least, one would not pin down any specific area.

Figure 5 represents the 14/00Z 12 through 48 hour forecast and verification tracks. It is quite apparent that the forecasts are converging across eastern Texas through Arkansas and Missouri into Illinois. General recurvature remains in Arkansas with a close grouping at 36 hours in eastern Illinois. Even though the LFM had a more southern 500 mb track, its surface positions were relatively close to the others. In addition, the LFM surface pressures verified better than the other models. This is an example of the upper levels not being well forecasted but the surface ending up close to reality. The SPM remained the most consistent model with very little change from the previous run.

Figure 6 is the 14/12Z initial through 36 hour forecast and verification tracks. Notice again how closely grouped the tracks were, becoming even closer than the previous run. This run strongly suggests that the surface low track will be through Arkansas into eastern Illinois. Notice, however, that while the surface low is similar in value for all models, the 36 hour NGM forecast again pulls the path west while the LFM heads a bit east. This seems to be a consistent tendency at the longer forecast ranges. Again, the SPM was the most consistent model with minor changes from the previous run.

4. Thickness Fields

The temperature structure of the atmosphere has probably the most significant impact on winter storm forecasts, more than any other single parameter. It indicates where the rain/snow line might occur and where the heaviest snow will likely fall. This is because snow production favors certain temperature regimes. In a gross way, (which works fairly well) the 531 to 537 thickness band is normally used as a conditional indicator of

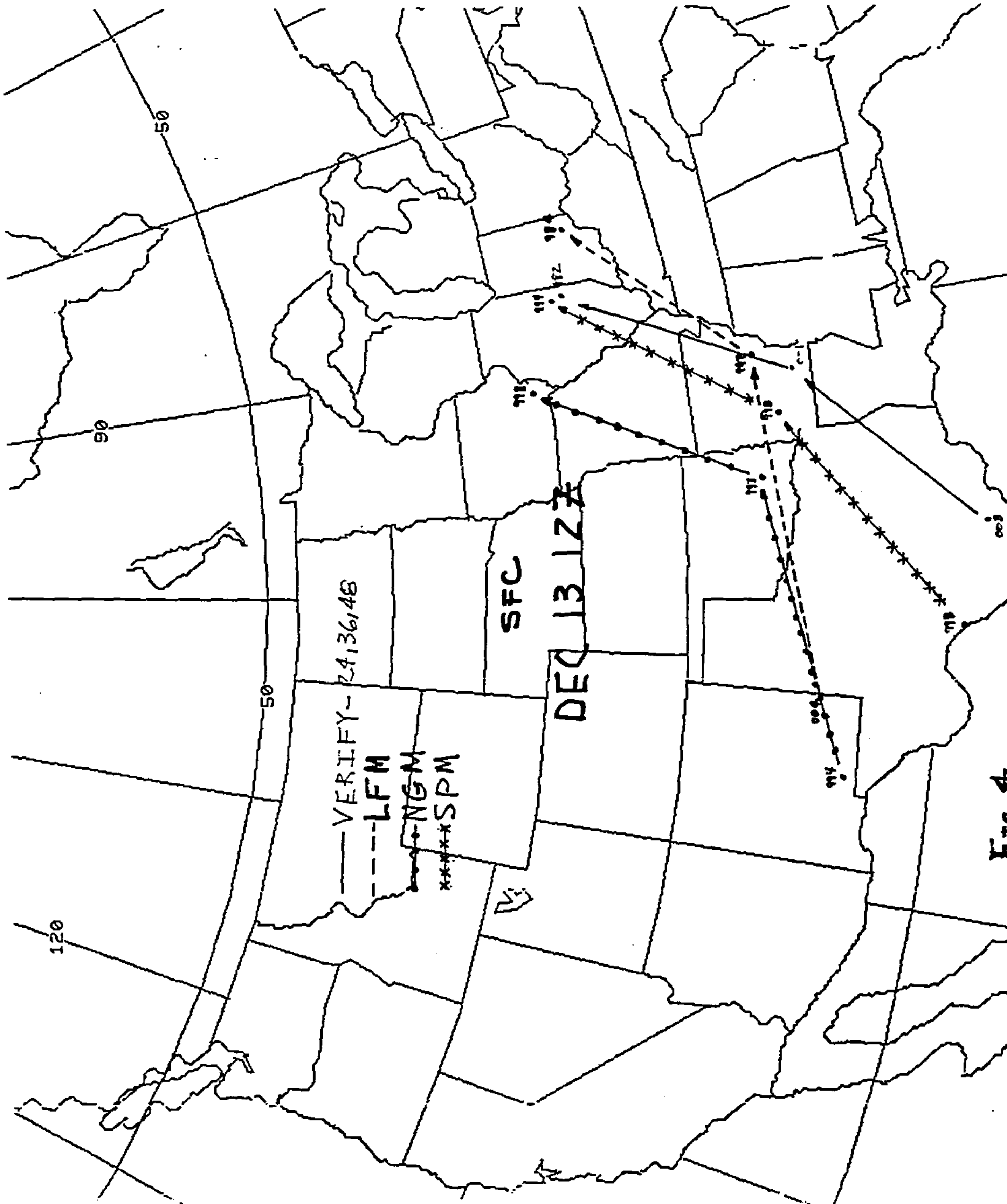



FIG 4

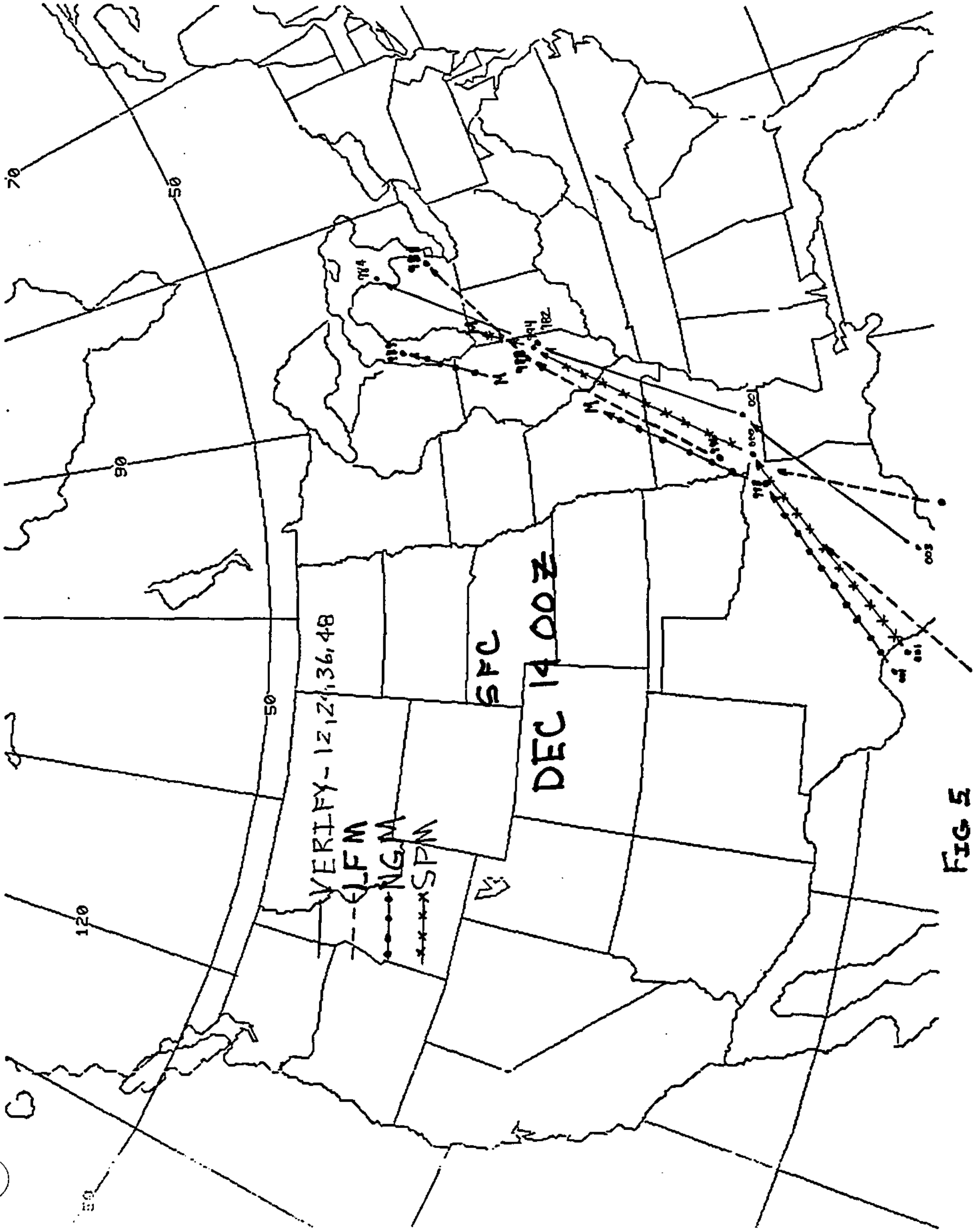



FIG 5

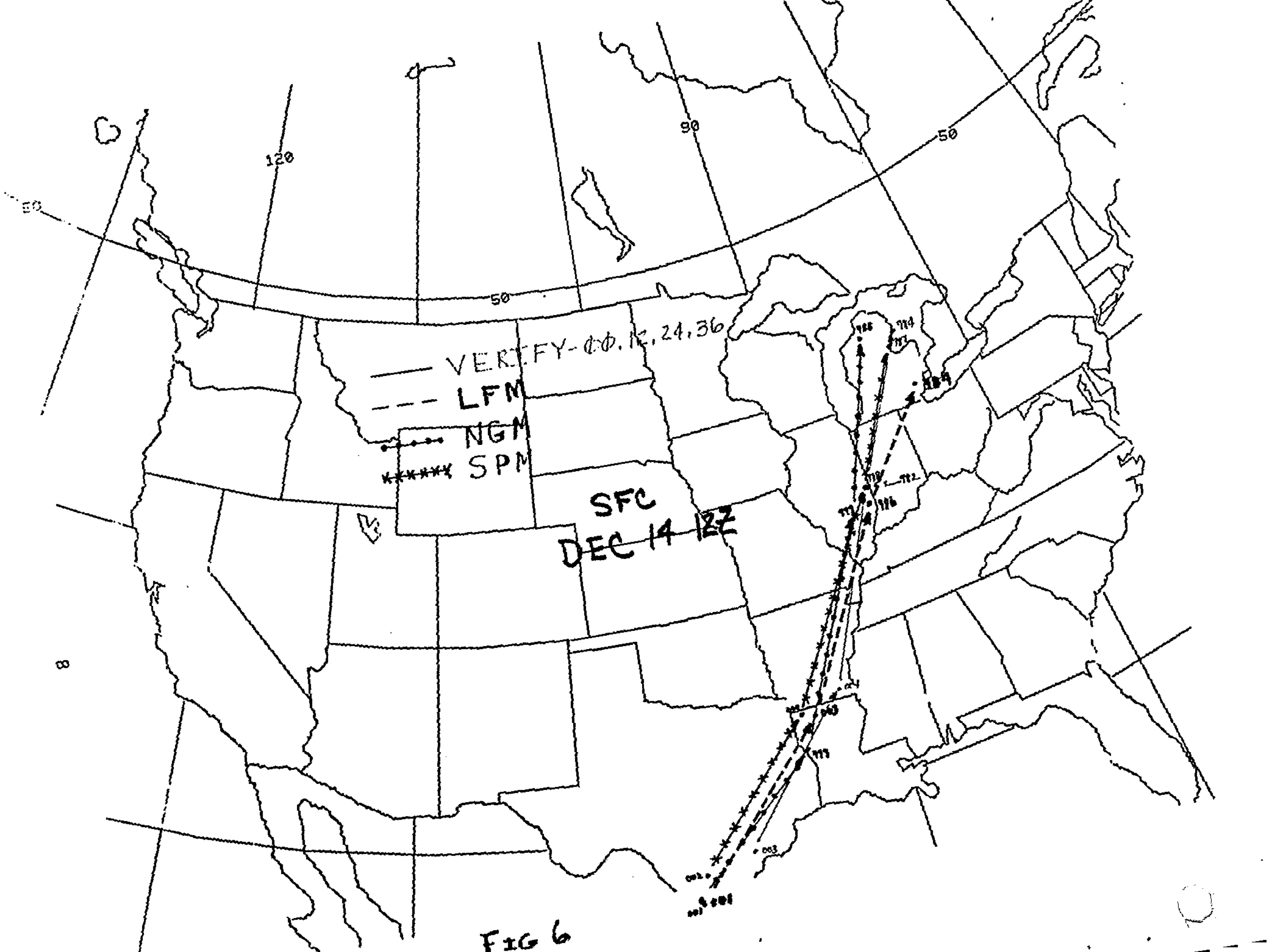



FIG 6

heavy snow. On the following 4-panel figures, this 531 to 537 thickness band has been shaded. The upper left panel of the 4-panel figures is verification, the upper right-LFM, lower left-NGM, and lower right-SPM.

Figures 7, 8, and 9 are the 24, 36 and 48 hour thickness forecasts from the 13/12Z run respectively. The fields from 36 to 48 hours would be the most important in considering the timing of significant snow. The 24 hour forecasts of Figure 7 were in reasonable agreement with each other, indicating that the snow bands would occur across southeast Iowa. As noted that the NGM had the warmest bias across this area while the SPM verified the best.

Figure 8 shows a considerable difference between the NGM/SPM and the LFM. The warm bias of the NGM is very noticeable as the SPM took a more compromising position. The LFM verified very well this time, but why? Did it have anything to do with the southern upper air track? Similar observations hold for Figure 9 at the 48 hour time frame with the NGM still being too warm.

Figures 10, 11, and 12 are the 12, 24, and 36 hour forecasts from the 14/00Z run respectively. At this point, in trying to pinpoint the timing of heavy snow, it would appear that the 15/00Z forecast would be most important. From the previous run, considerable warming was noted at the 15/00Z forecast (Figure 8). Looking at Figure 11, this occurred again, with the LFM indicating similar results. As seen in other forecasts, the SPM was most consistent. Still, ALL THREE MODELS WERE TOO WARM at 24 and 36 hours with the NGM/LFM the warmest.

Figures 13 and 14 are the 12 and 24 hour forecasts from the 14/12Z run. Prominent is the close grouping of the 531 to 537 thickness bands from each model across southeast Iowa. As seen in all these thickness forecasts, divergence between model output beginning to occur at the 24 hour forecast period. In this run, the LFM appeared to be too warm when compared to the NGM/SPM. Even so, ALL MODELS VERIFIED TOO WARM. While, the models did forecast the correct precipitation type (which in some cases is THE most important forecast), the handling of the heavy snow band based on thickness was not the best.

## 5. Snow Area Evolution

Figures 15 through 18 are snapshots of moderate to heavy snowfall at 3-hourly intervals gleaned from surface observations. Figure 15 depicts the 06Z, 09Z, 12Z, and 15Z snow areas and surface low position. Note the westward expansion of snowfall into southwest Kansas, southeast Colorado, and all of the Texas Panhandle at 09 and 12Z, then the sharp contraction at 15Z into central sections of Kansas and Oklahoma. Looking east into Missouri, snow breaks out at 12Z and expands into STL at 15Z. Note the distance between the snow and the weak surface low.

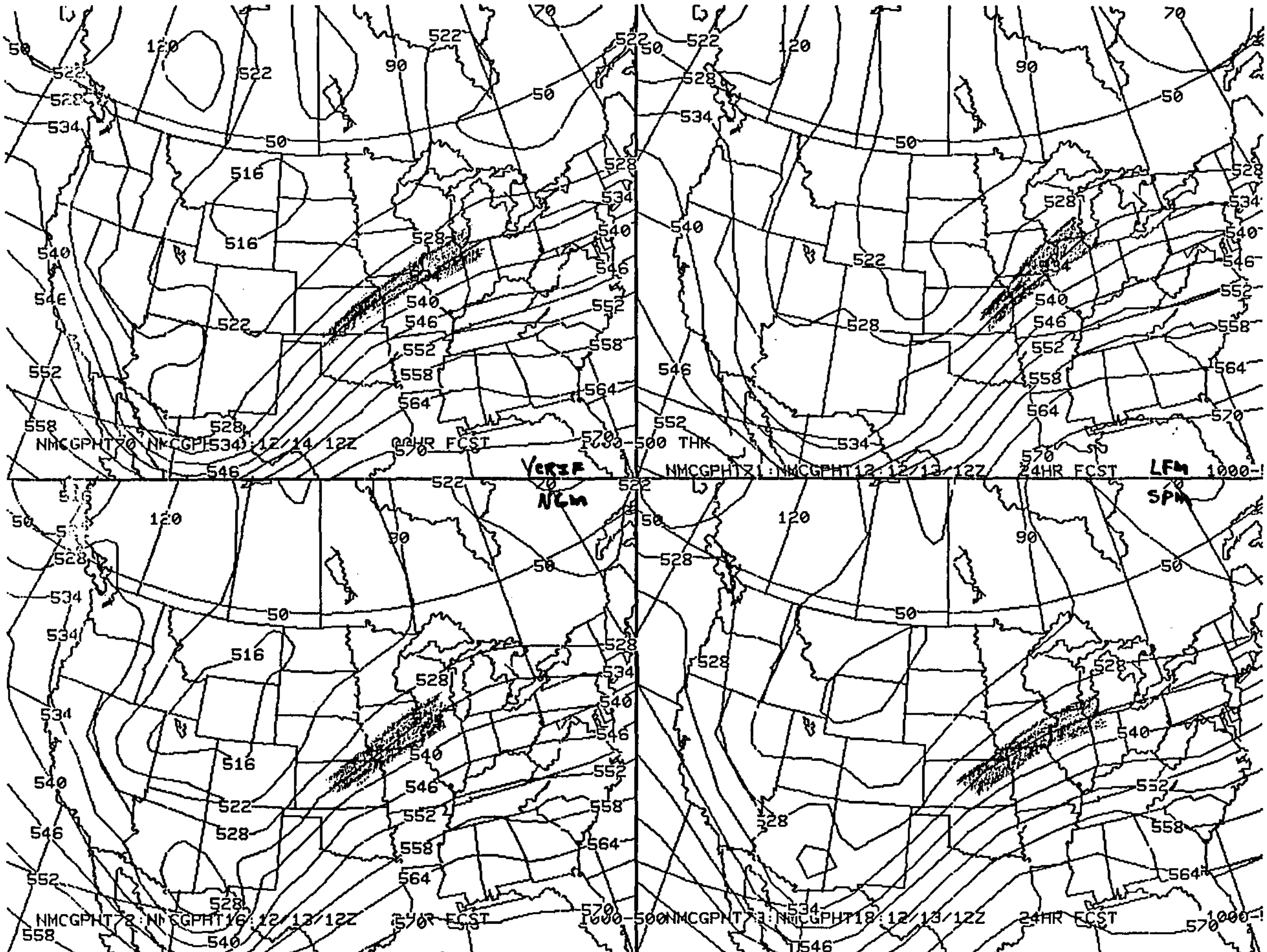

NMCGPHT70 NMCGPH 12/14 12Z 00HR FCST
1000-500 THK
VERIF
NGM
NMCGPHT71:NMCGPHT12:12/13/12Z 24HR FCST LFM 1000-
LFM
SPM
NMCGPHT72:NMCGPHT16:12/13/12Z FCST
NMCGPHT73:NMCGPHT18:12/13/12Z 24HR FCST 1000-

FIG 7

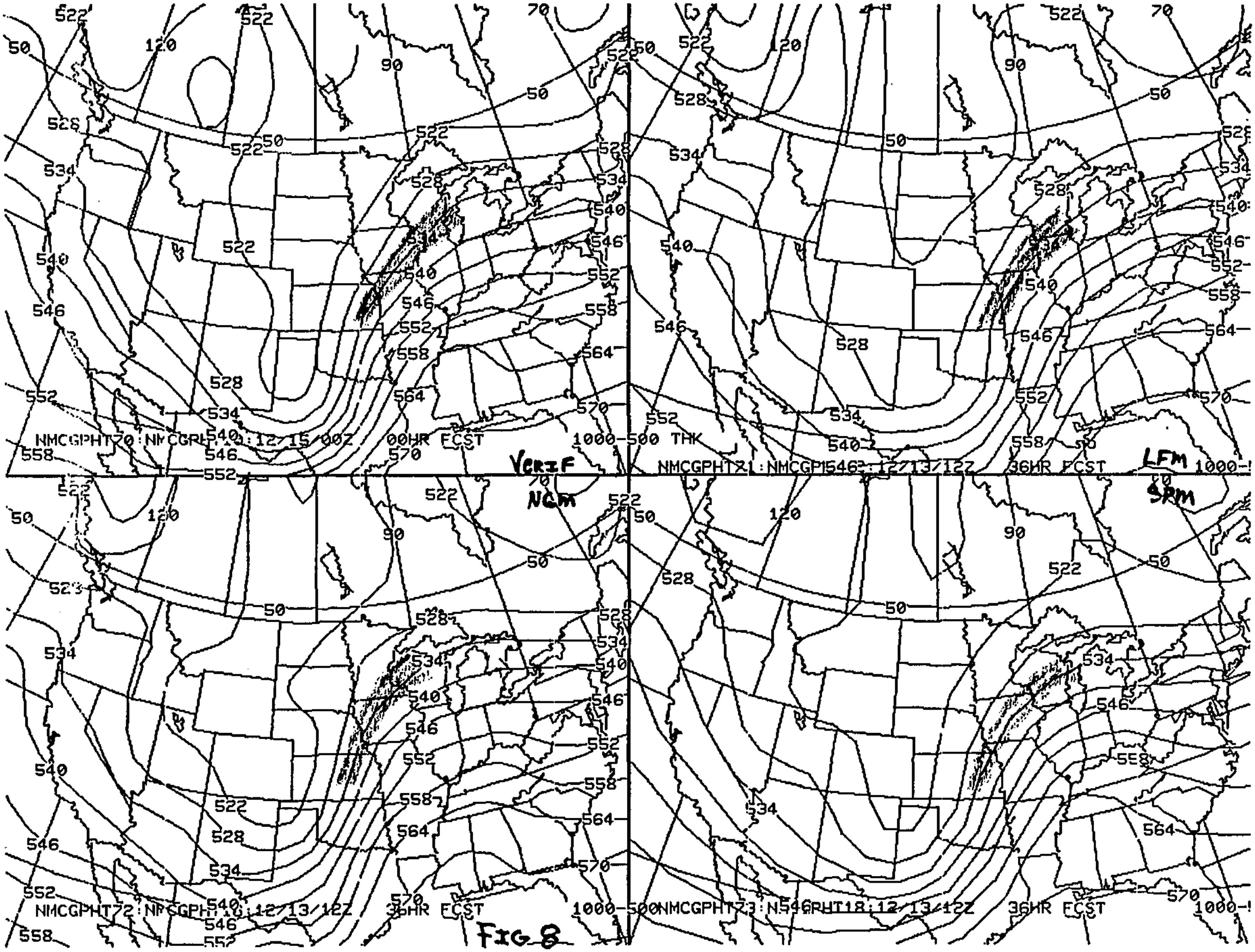

NMCGPHT70:NMCGPHT10:12/15/00Z 00HR FCST 1000-500 THK
VERIF
NGM
NMCGPHT71:NMCGP...:12/13/12Z 36HR FCST
LFM
SPM
NMCGPHT72:NMCGPHT10:12/13/12Z 36HR FCST
NMCGPHT73:N...PHT18:12/13/12Z 36HR FCST

FIG 8

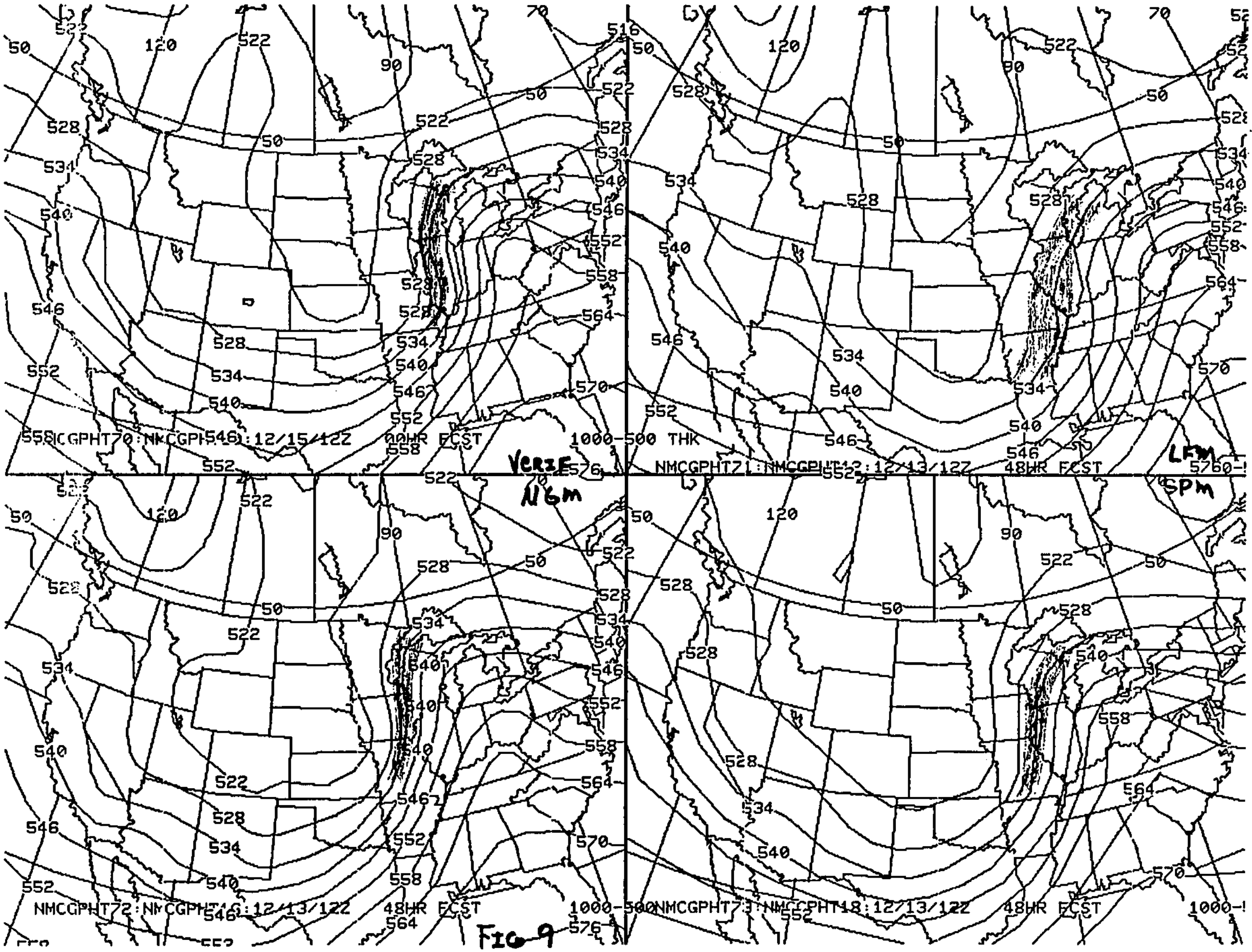

NMCGPHT70:NMCGPHT6:12/15/12Z 00HR FCST 1000-500 THK
VERIF
NGM
NMCGPHT71:NMCGPHT12:12/13/12Z 48HR FCST
LFM
SPM
NMCGPHT72:NMCGPHT16:12/13/12Z 48HR FCST 1000-500
NMCGPHT73:NMCGPHT18:12/13/12Z 48HR FCST 1000-

FIG 9

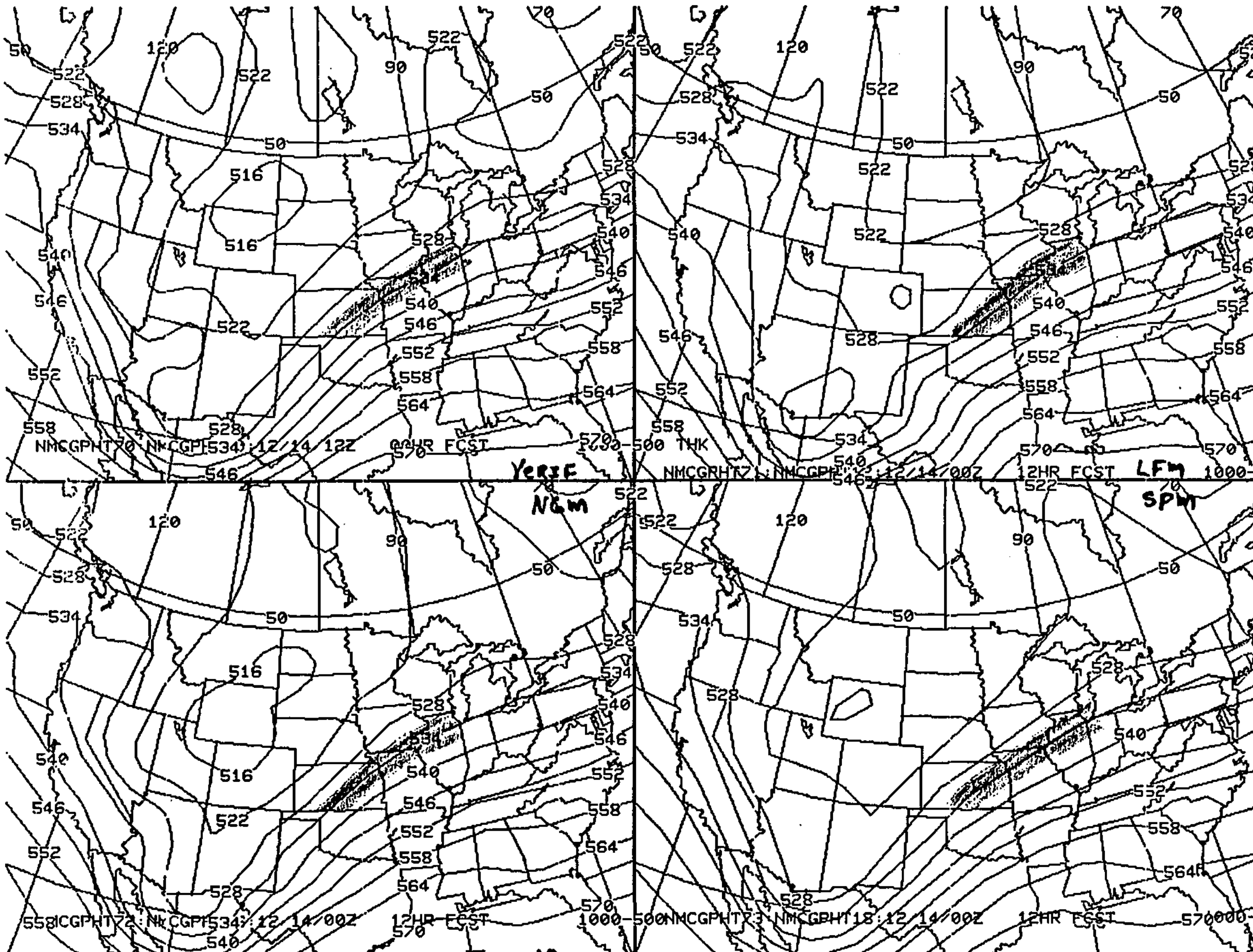

NMCGPHT70 NMCGPI 12/14 12Z 00HR FCST 1000-500 THK
VERIF
NGM
NMCGPHT71 NMCGPH 12/14/00Z 12HR FCST
LFM
SPM
NMCGPHT72 NMCGPI 12/14/00Z 12HR FCST 1000-500
NMCGPHT73 NMCGPHT18 12/14/00Z 12HR FCST

FIG 10

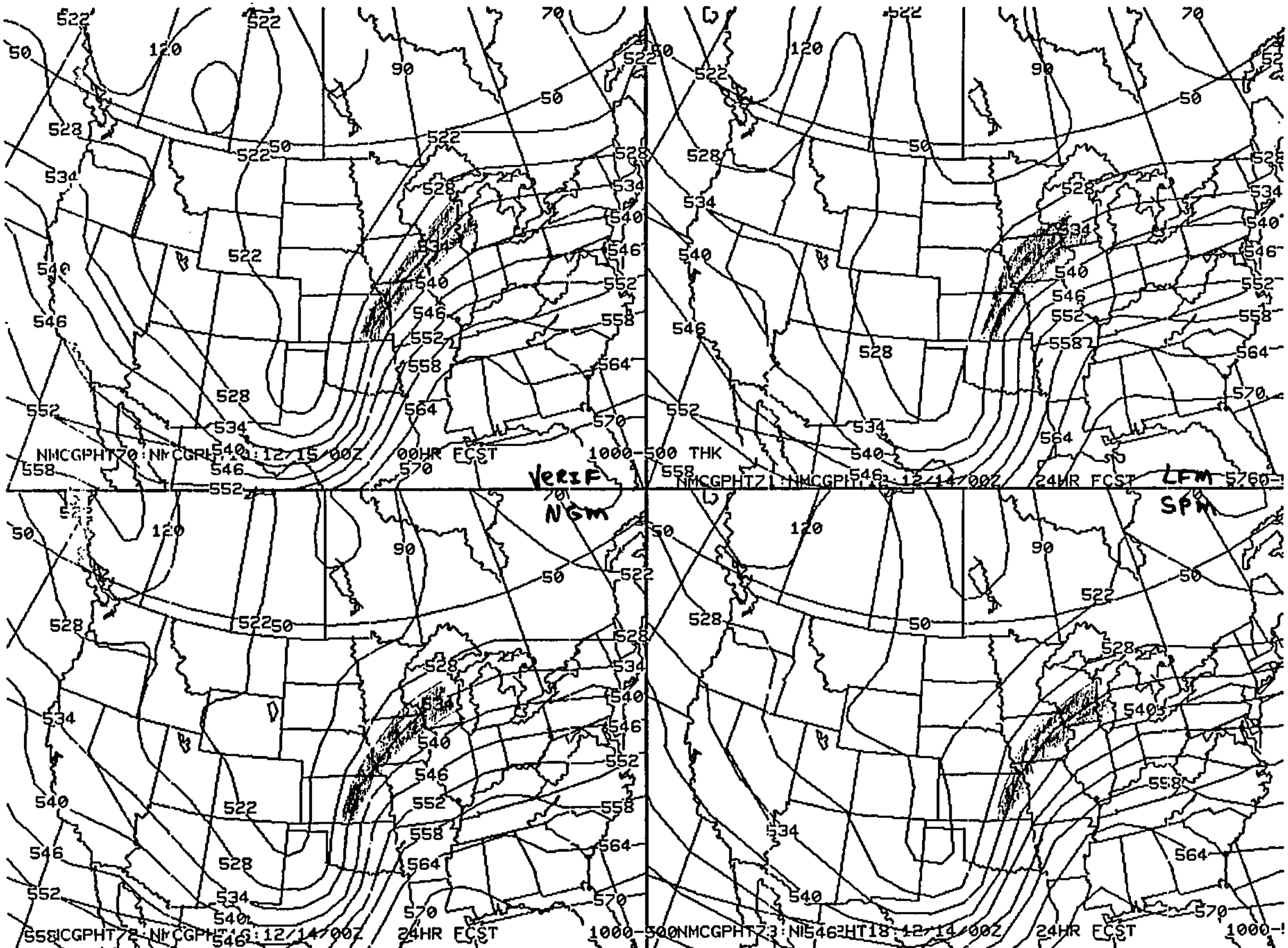
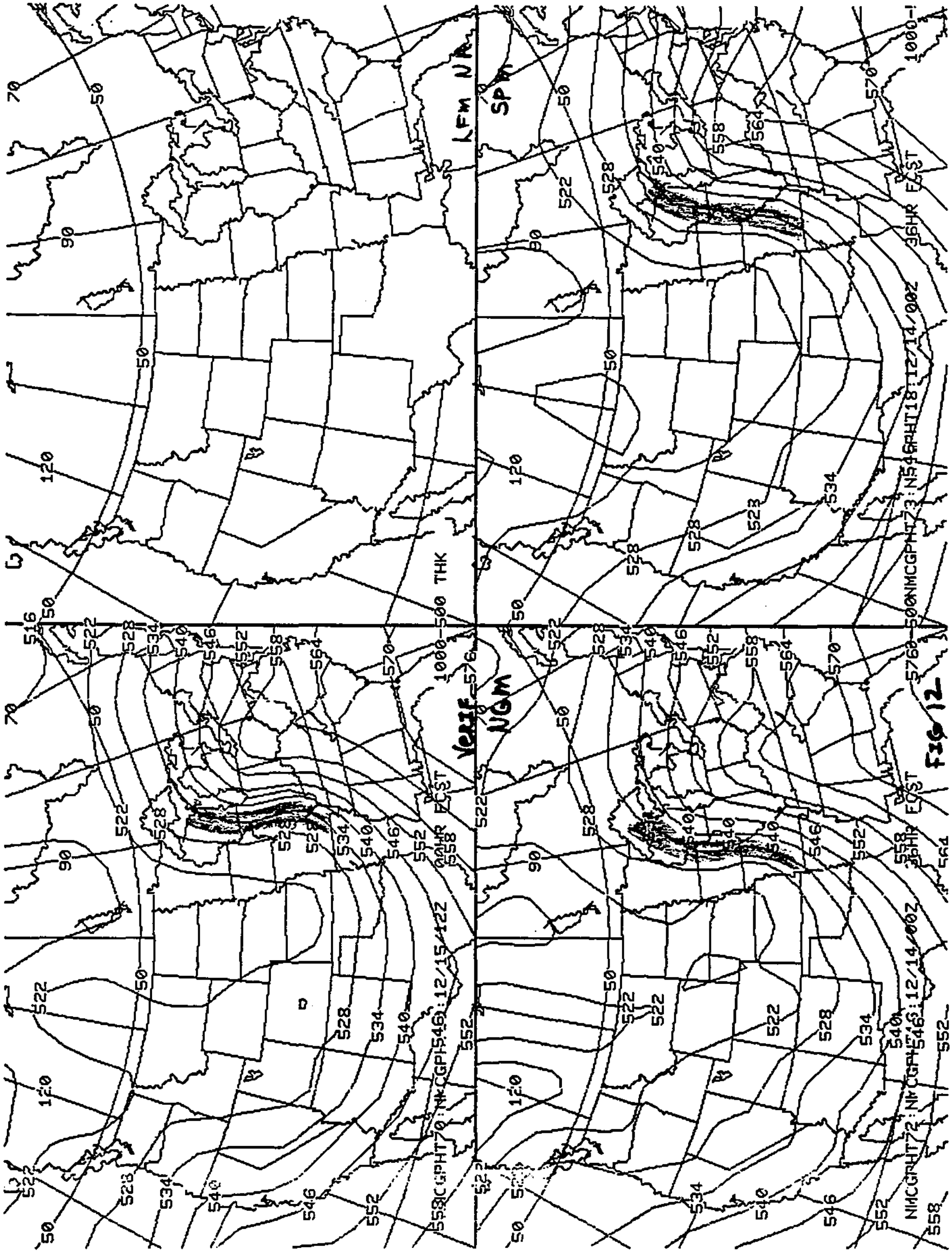
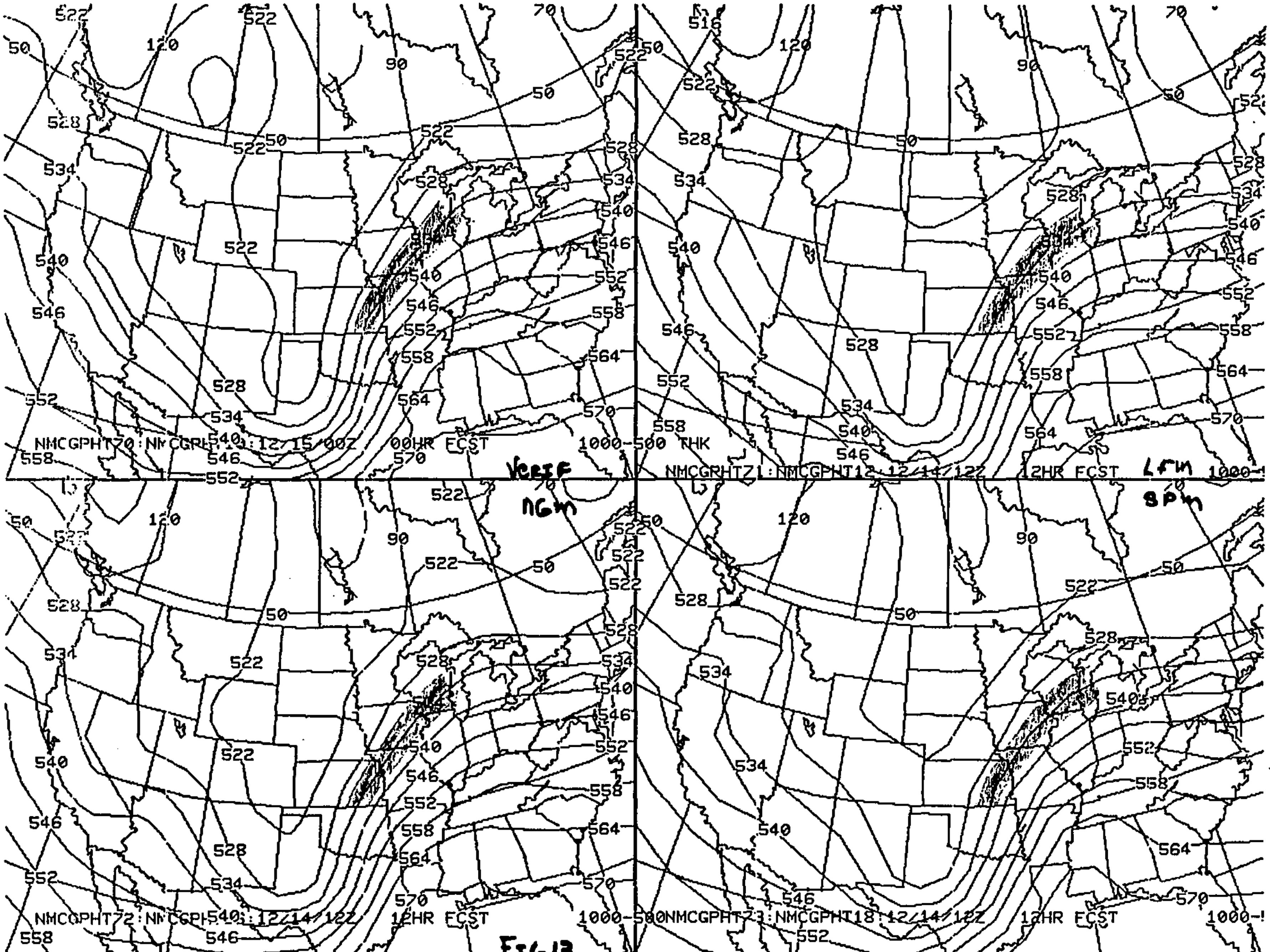

12/15/00Z 00HR FCST
1000-500 THK
VERIF
NGM
12/14/00Z 24HR FCST
LFM
SPM
12/14/00Z 24HR FCST
1000-500
12/14/00Z 24HR FCST

FIG 11


LFM NR
SPM
VERIF
NGM
1000-500 THK
00HR FCST
36HR FCST
Fig 12


NMCGPHT70:NMCGPHT10:12/15/00Z 00HR FCST 1000-500 THK
VERIF
NGM
NMCGPHT71:NMCGPHT12:12/14/12Z 12HR FCST 1000-
LFM
8PM
NMCGPHT72:NMCGPHT16:12/14/12Z 12HR FCST 1000-500
NMCGPHT73:NMCGPHT18:12/14/12Z 12HR FCST 1000-


FSG13

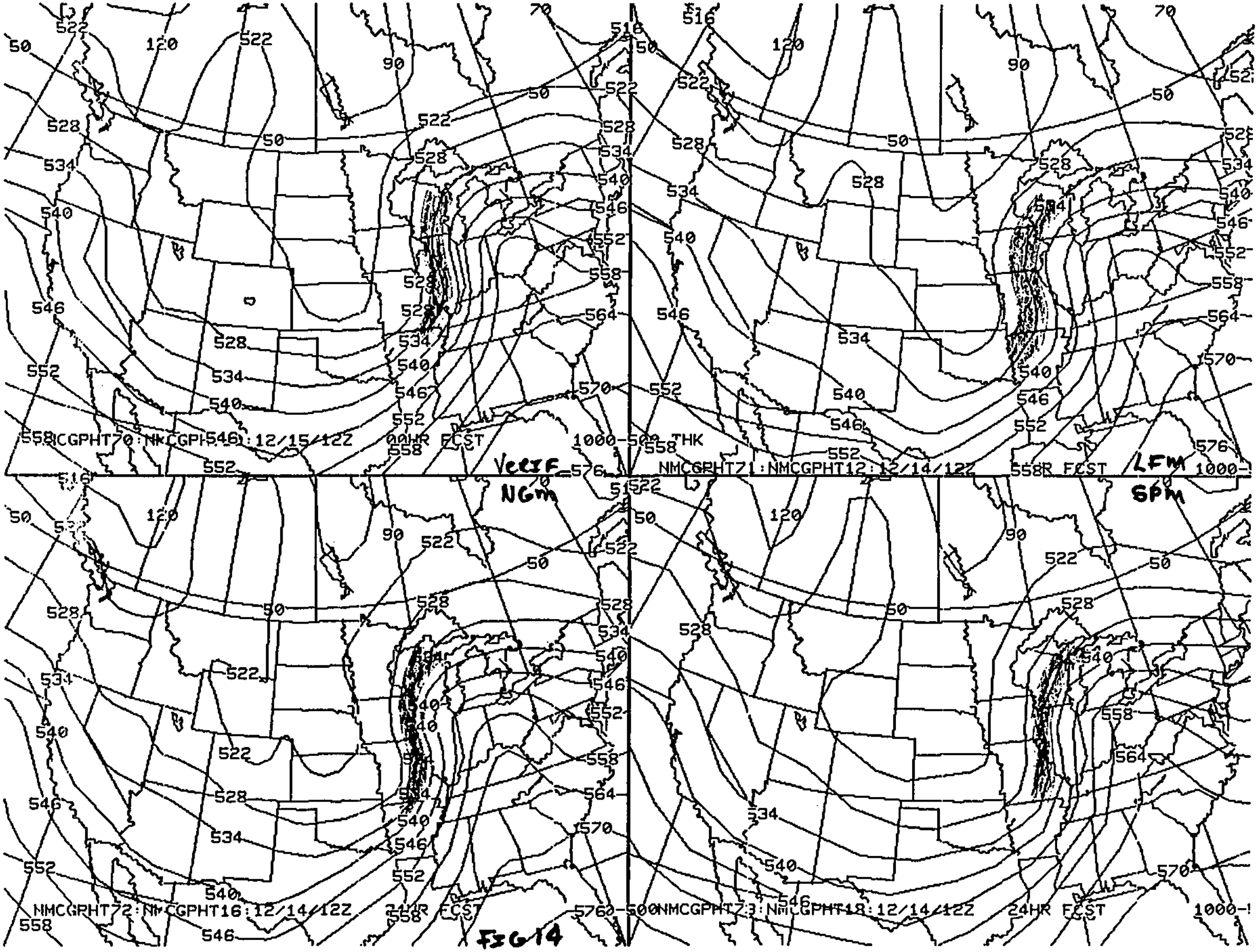

NMCGPHT70:NMCGPH  :12/15/12Z 00HR FCST 1000-500 THK
VeRIF
NGM
NMCGPHT71:NMCGPHT12:12/14/12Z  HR FCST 1000-
LFM
SPM
NMCGPHT72:NMCGPHT16:12/14/12Z 24HR FCST
NMCGPHT73:NMCGPHT18:12/14/12Z 24HR FCST 1000-

FIG 14

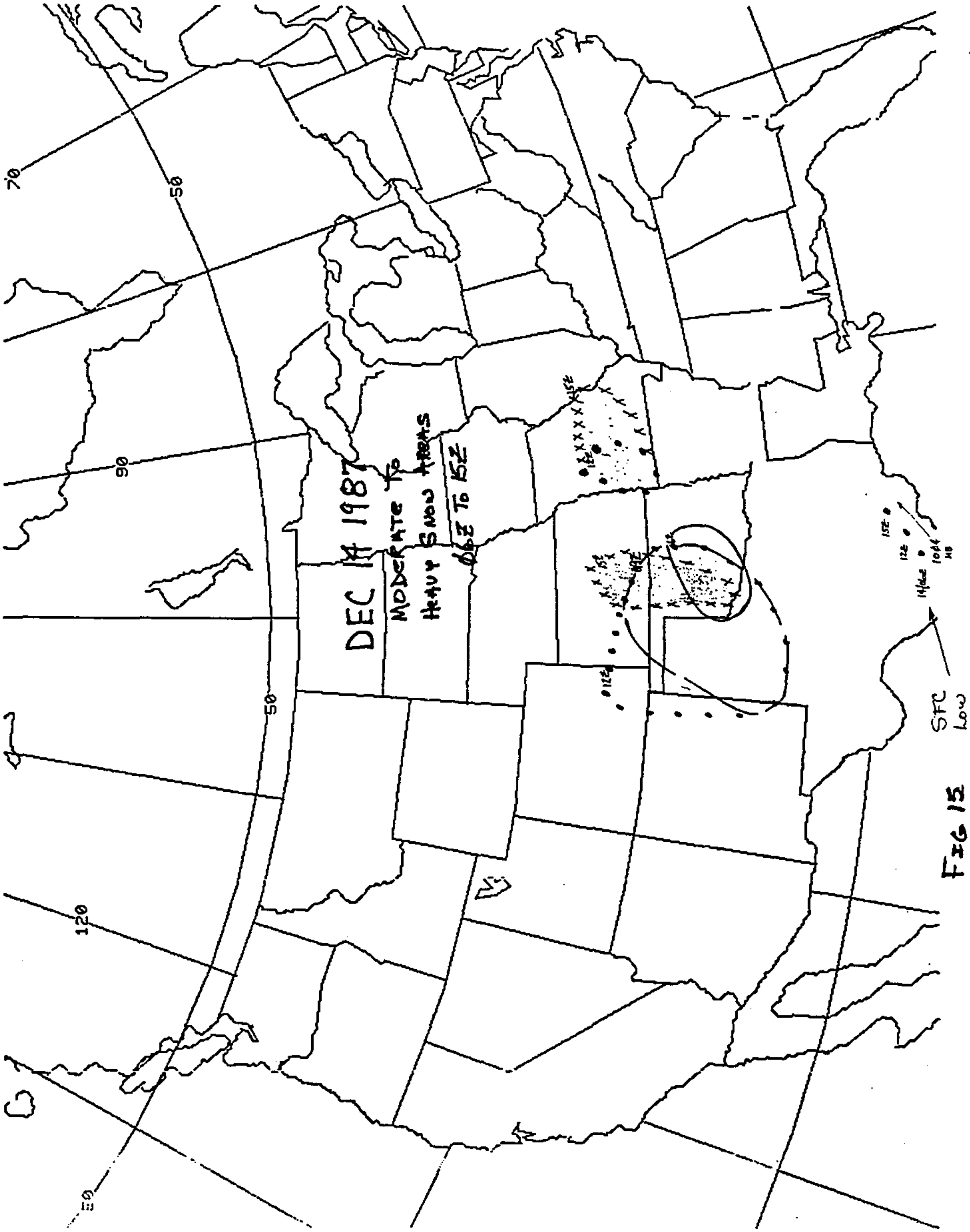

DEC 14 1987
MODERATE TO
HEAVY SNOW AREAS
06Z TO 15Z
SFC
Low
70
50
90
120
60

FIG 15

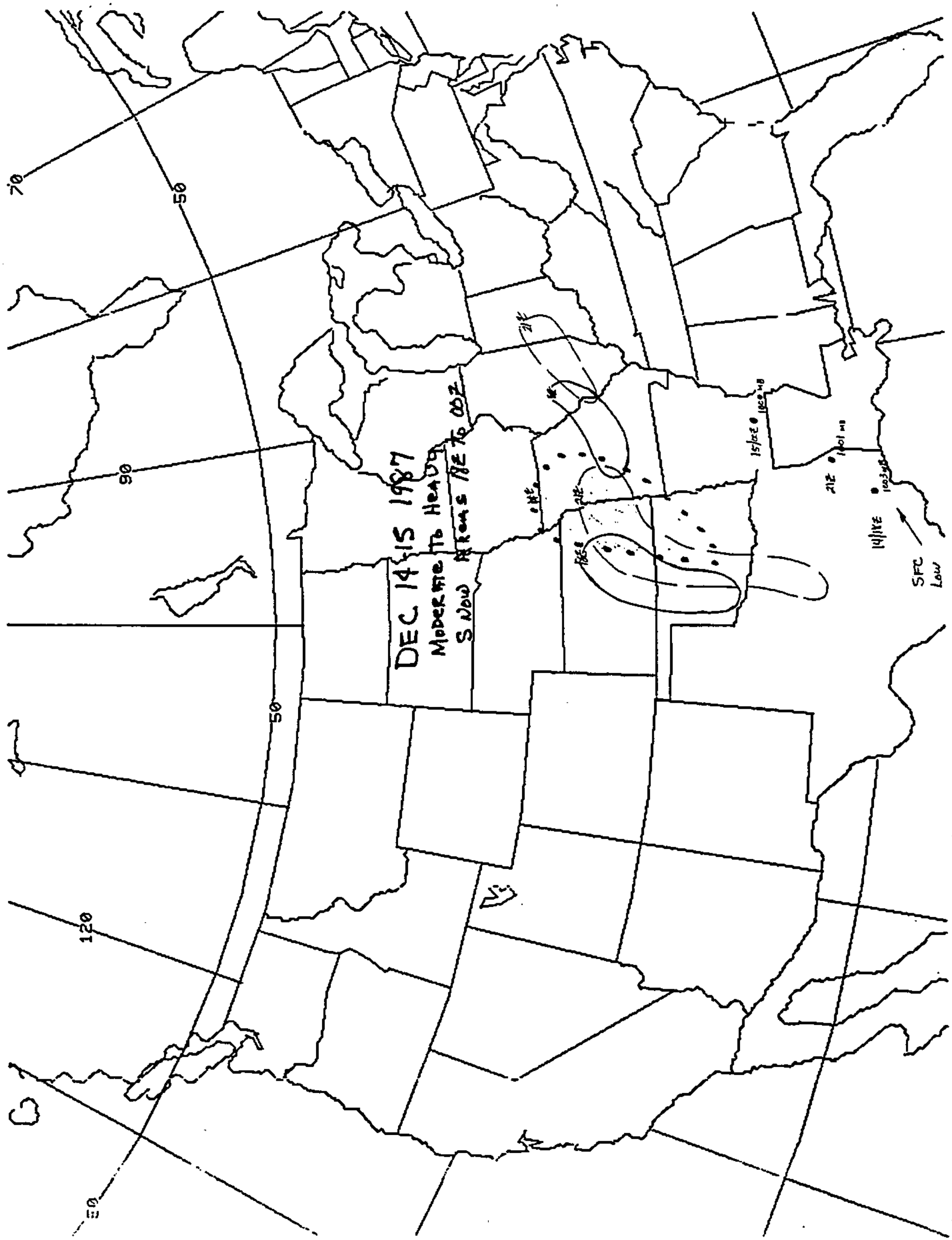

70
50
90
50
120
DEC 14-15 1987
MODERATE TO HEAVY
SNOW ACROSS 18Z TO 00Z
SFC LOW

FIG 16

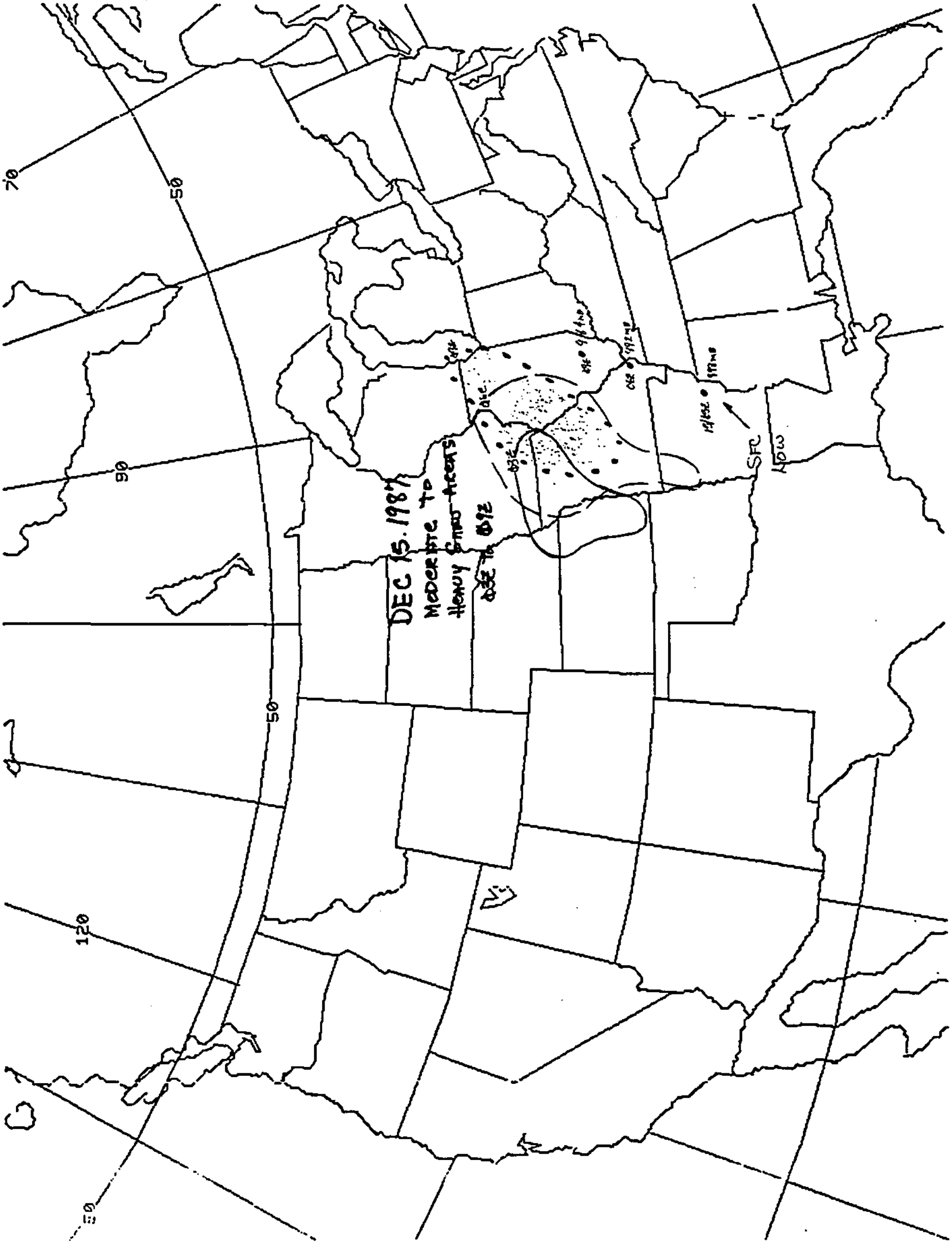

DEC 15 1987
Moderate to
Heavy Snow Accums
03Z to 09Z
SFC
LOW
70
50
90
50
120

FIG 17

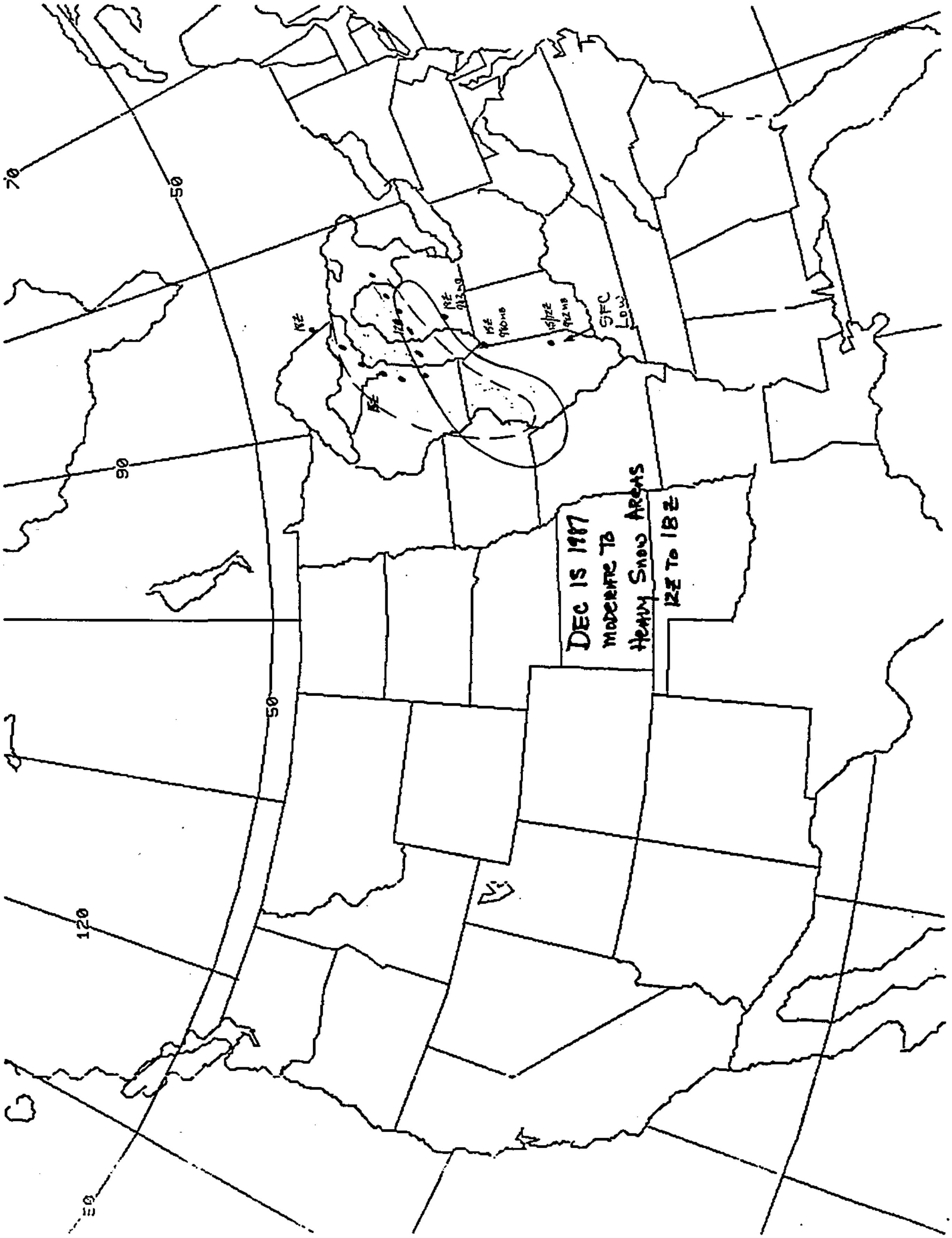

70
50
90
120
SFC LOW
DEC 15 1987
MODERATE TO
HEAVY SNOW AREAS
12Z TO 18Z

FIG 1B

Figure 16 shows movement of the western snow area into eastern Kansas and western Missouri to Iowa. The eastern area moves into Illinois and Indiana dissipating beyond 21Z. Again, note the distance between the snow area and surface low.

Figure 17 includes the 15/03Z snow area to 09Z. Looking at the 03Z depiction, notice how the area expands more eastward rather than northward as compared to Figure 15's 00Z area. This more east/northeast expansion continued through 09Z as the surface low distance closed between snow field and location. It was not until 06Z that the standard rule of thumb for distance between surface low and heavy snow came into play some six to nine hours before maximum intensity was observed.

Figure 18 shows significant snowfall from 12Z to 18Z as the storm pulled away from the state. The distance between the snow areas and the surface low decreased to a minimum at 15Z, the lowest pressure of the storm.

## 6. MAGIC CHART

Figure 19 is the composite trajectory 850 mb temperature and 700 mb net vertical displacement (NVD) chart or "MAGIC CHART" as devised by Sangster and Jagler (also see Chastin, 1989). This chart is valid for a 12 hour period ending 14/12Z. The forecast did fairly well, indicating the significant snow in western Oklahoma and southern Kansas stretching into Missouri. Maximum snowfall was indicated in west central through northeast Oklahoma under the +100 vertical displacement. A check of Figure 22 indicates maximum observed snowfall.

Figure 20 is the "MAGIC CHART" valid for the 12 hour period ending 15/00Z. The forecast is for continued heavy snowfall in central Oklahoma northeast into southeast Kansas and west central Missouri. Observe that moderate snowfall (+60 to +80 mb band) could be expected nears the southern Iowa border.

Figure 21 is valid for the 12 hour period ending 15/12Z. The heavy snow forecast has pivoted out of Oklahoma and Kansas quite rapidly arcing across southeast Iowa. Maximum snowfall would be expected to occur in extreme southeast Iowa into northern Illinois.

The heaviest snow usually occurs along the -3°C to -5°C band where the NVD is greater than 80 mb. Figures 19, 20, and 21 highlight the +80 NVD and -3°C boundaries. Figure 22 displays the observed snowfall for this event.

## 7. Comments and Suggestions

The one significant impression gleaned from this post-analysis is that there often is not good continuity in how the models handle storm tracks, both from a model (run to run) and a forecasting and/or observed aspect. It would seem that during a storm situation, a simple chart of all three model 500 mb (or 700 mb) forecast tracks per run could be drawn quite quickly.

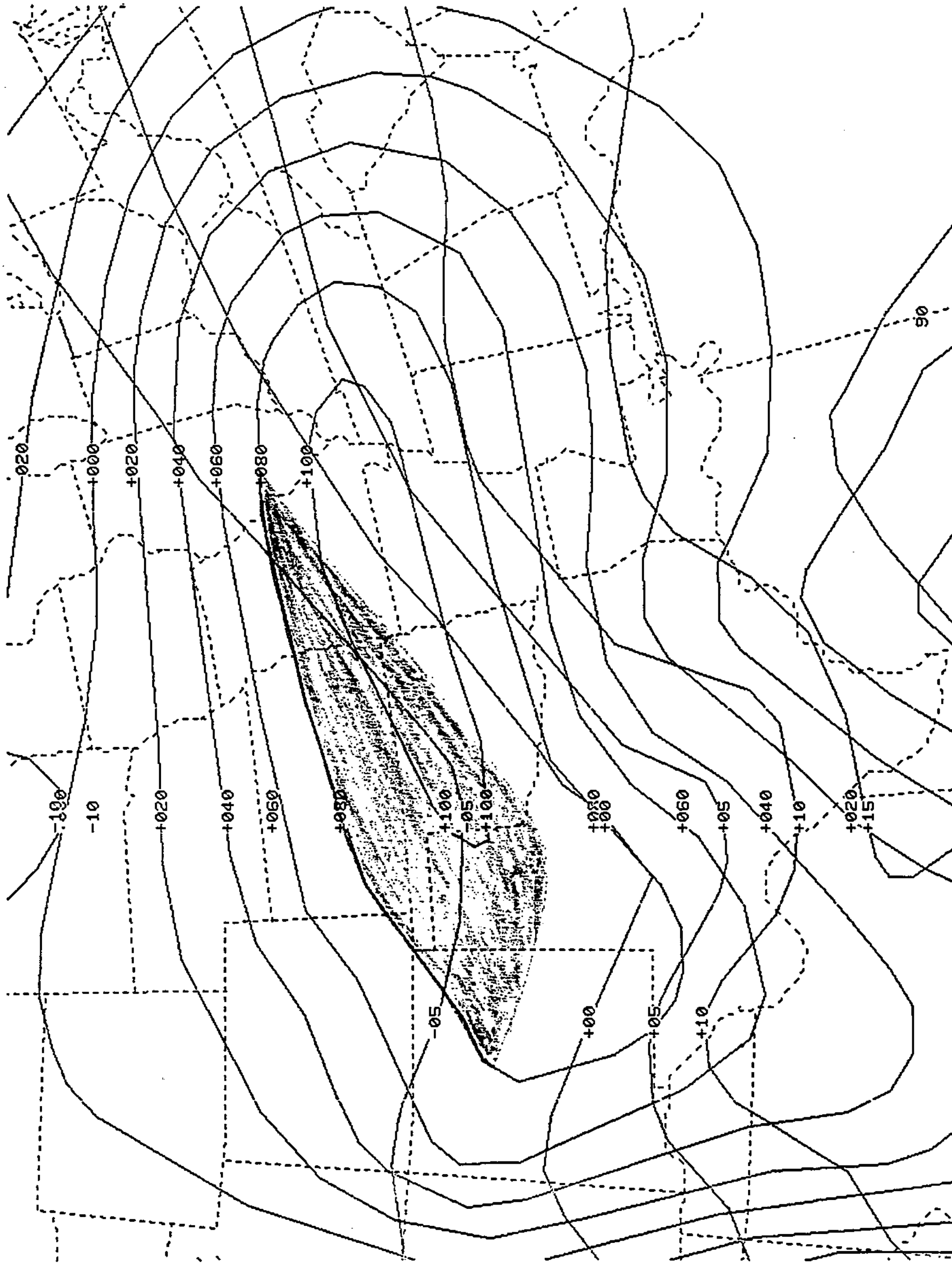
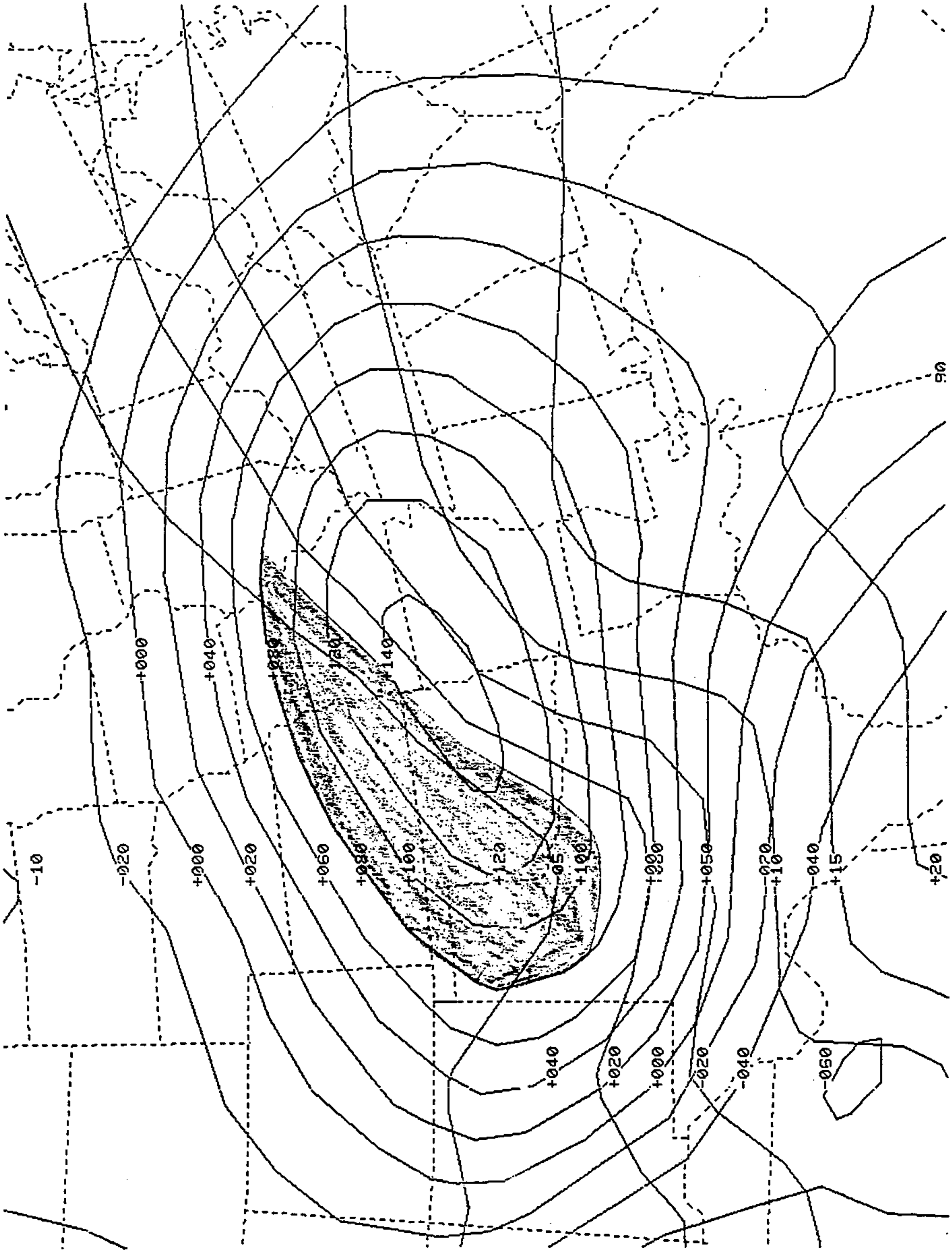

-020
+000
+020
+040
+060
+080
+100
-100
-10
+020
+040
+060
+080
+100
-05
+100
+080
+00
+060
+05
+040
+10
+020
+15
-05
+00
+05
+10
90

Fig 19



-10
-020
+000
+020
+060
+080
+100
+120
+100
+030
+050
-070
+10
-040
+15
+20
+000
+040
+080
130
140
+040
+020
+000
-020
-040
-050
90


FIG 20

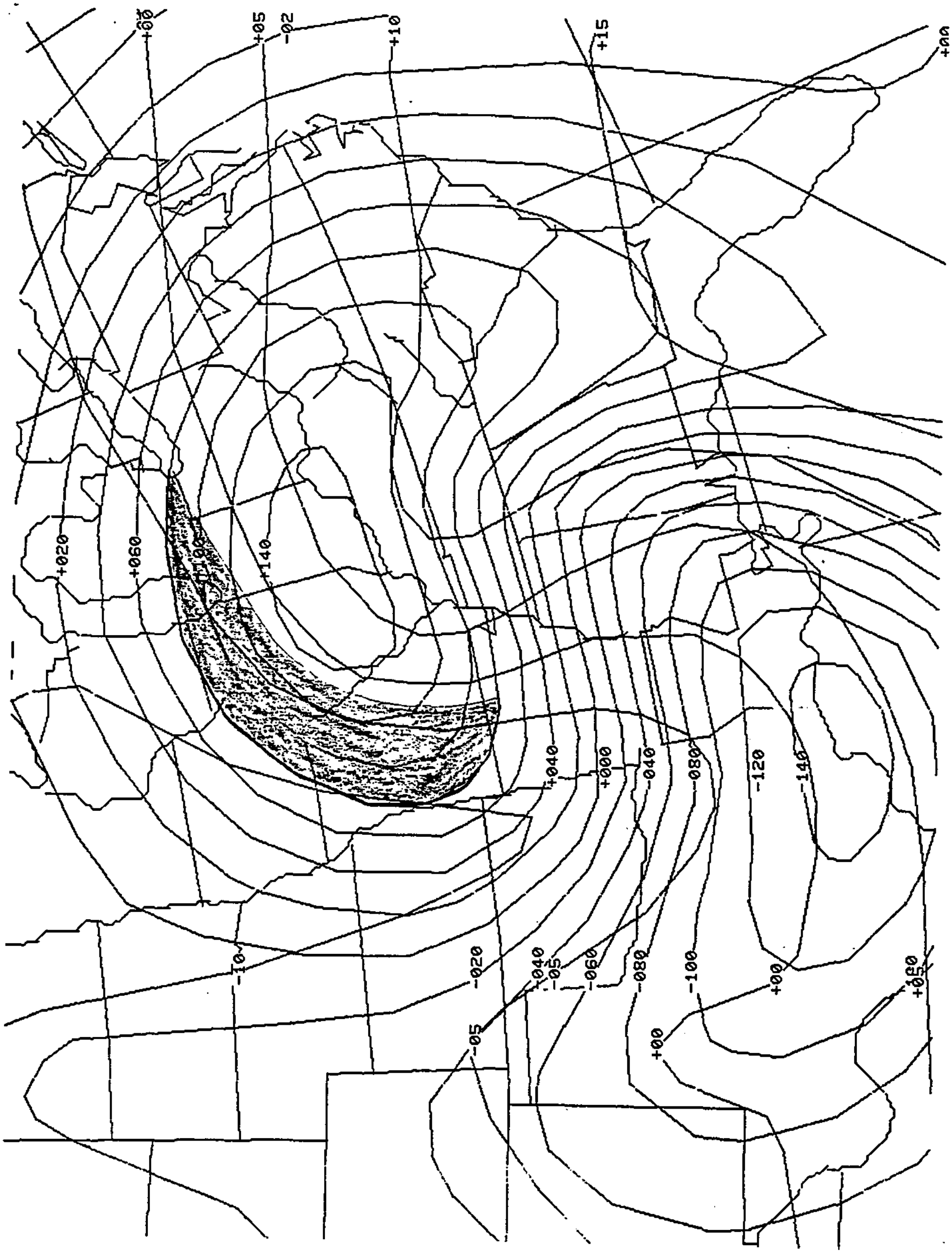
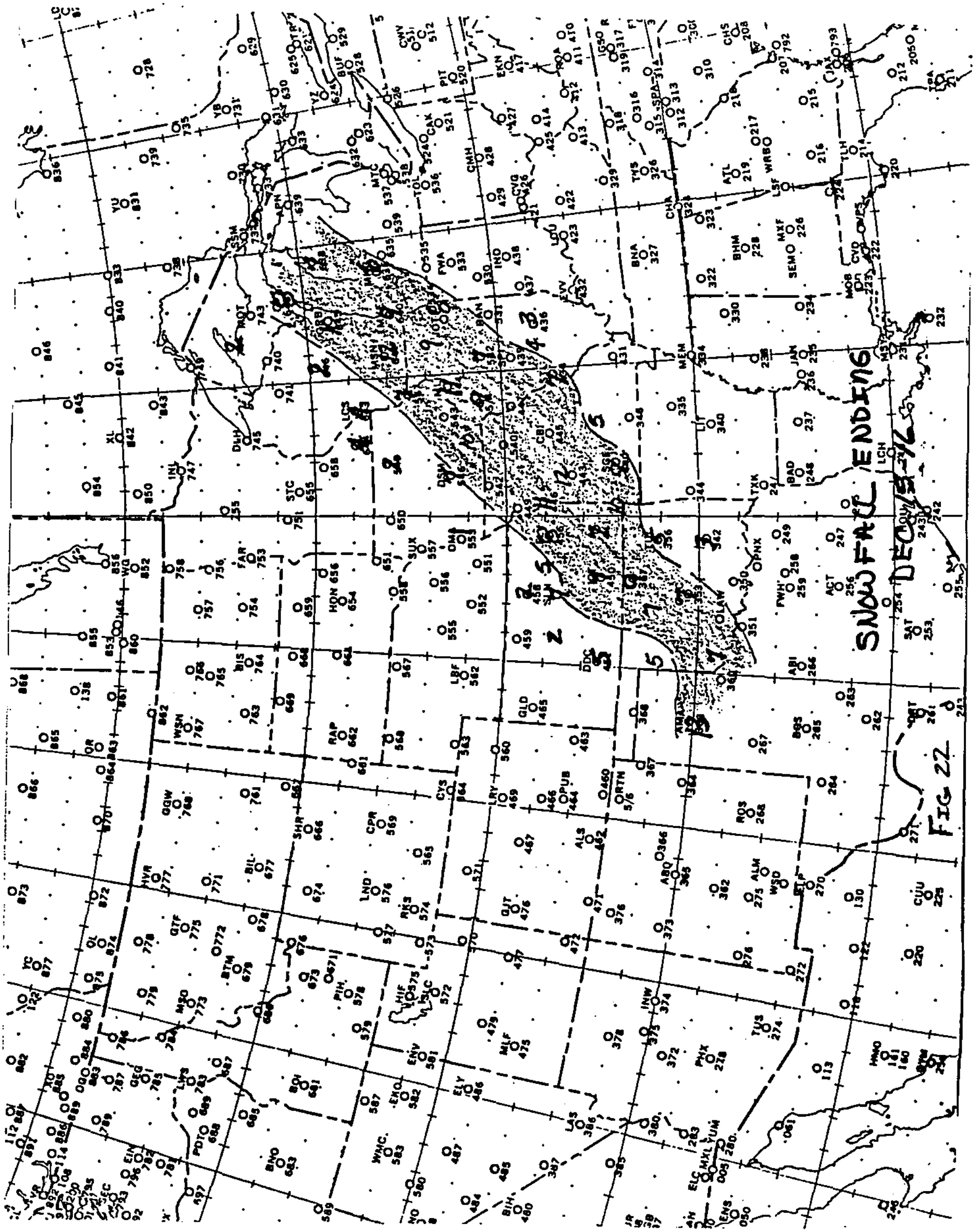


FIG 21


SNOWFALL ENDING DEC 15-16
FIG 22

Starting at the 60 or 48 hour time frame, forecasters would have several track charts to observe how the models were handling the storm. This would be done for the surface low also, or other important parameters if deemed necessary. It would make a good briefing tool and generate (hopefully) confidence in the best model.

One important aspect noted by Weber (1978) is recurvature point. For most Iowa storms, the point of recurvature will eventually determine were the heavy snow band will occur. Track charts constructed for each run should highlight where this will occur.

It appears from this storm and gross checks of others (personally done) that the "MAGIC CHART" has merit as a heavy snow forecasting aid, EVEN THOUGH THE LFM MAY BE OFF ON 500 MB AND SURFACE TRACKS.

Lastly, an ongoing chart of moderate to heavy snow areas drawn at 3-hourly intervals would prove very helpful once the storm is underway. It would quickly relate the surface low position to snowfall, verify pops, and help correlate satellite data to beginning and ending times (just as important as the storm itself).

## 8. References

Chastin, P. R., 1989: The Magic Chart for Forecasting Snow Amounts. Nat. Wea. Dig., 14, 20-22.

Sangster, W. E. and E. C. Jagler, 1985: The (7WG,8WT) "Magic" Chart, Central Region Technical Attachment 85-1, NWS Central Region, Scientific Services, Kansas City, MO.

Weber, E. M., 1978: Major Midwestern Snowstorms. Preprints, Conf. on Weather Forecasting and Analysis and Aviation Meteorology, 30-37.

CRH SSD
CRARP 99-2

CENTRAL REGION APPLIED RESEARCH PAPER 99-2

# RELIABILITY OF PROBABILITIES

Craig M. Edwards
National Weather Service Forecast Office
Indianapolis, Indiana

Since 1966 the National Weather Service's forecasts have supplemented verbal statements of precipitation chances with numerical probabilities of precipitation (POP's). In a survey conducted by Curtis and Murphy in 1984, respondents favored the use of numerical POP's over verbal statements alone by a ratio of three to one.

In using numerical probabilities, the NWS forecasts quantify the chances of measurable precipitation (0.005 inches or greater). Clients with projects and programs sensitive to wet weather, as well as the general public, have likely based numerous decisions on the POP forecast. The local issuing office's previous track record along with clients confidence in their continuing "success" lends some credibility to a rain or snow forecast.

The use of a specific probability is essentially the professional opinion of the meteorologist preparing the forecast. It is the probability of measurable rain or snow at any point in the forecast zone during the designated time period. As a very good "first guess," the forecaster frequently consults the Model Output Statistics (MOS) data from the LFM numerical forecast.

Some measure of reliability can be determined by examining a rather large sample of forecasts. This paper presents a review of forecasts made at the WSFO Indianapolis for March 1, 1987 through February 29, 1988. Forecasts by the local WSFO and the LFM MOS for three 12-hour periods, based on the 00Z and 12Z initial data are compared. Table 1 presents a cumulative distribution and verification of forecasts.

Two items provide the most striking contrast between MOS and the WSFO forecasts. First, through the course of the year, the MOS guidance issued 144 more 20 and 30 percent probabilities than the local office. Yet, combining the 20 and 30 percent POP's for both the local office and MOS guidance, they verified with measurable precipitation 25 percent of the time.

# PRECIPITATION PROBABILITY DISTRIBUTION

## MARCH 1987 - FEBRUARY 1988

WSFO IND

| PROB | 00 | 2-5 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RAIN | 6 | 5 | 34 | 39 | 68 | 65 | 73 | 73 | 49 | 43 | 27 | 23 | |
| FCST | 540 | 249 | 409 | 245 | 179 | 148 | 136 | 105 | 59 | 49 | 30 | 29 | |
| R/F | 01 | 02 | 08 | 16 | 38 | 44 | 54 | 70 | 83 | 88 | 90 | 79 | PCT |

LFM MOS

| PROB | 00 | 2-5 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RAIN | 1 | 7 | 34 | 76 | 62 | 80 | 74 | 59 | 42 | 29 | 24 | 17 | |
| FCST | 427 | 313 | 360 | 367 | 201 | 167 | 128 | 83 | 53 | 35 | 26 | 18 | |
| R/F | 00 | 02 | 09 | 21 | 31 | 48 | 58 | 71 | 79 | 83 | 92 | 94 | PCT |

| | 0-10 | 20-30 | 40-50 | 60-70 | 80-100 |
|---|---|---|---|---|---|
| LOCAL | 45/1198 | 107/424 | 138/284 | 122/164 | 93/108 |
| R/F | .04 | .25 | .49 | .74 | .86 |
| MOS | 42/1100 | 138/568 | 154/295 | 101/136 | 70/79 |
| R/F | .04 | .24 | .52 | .74 | .89 |
| PERCENT of Total Forecast | | | | | |
| LOCAL | .55 | .19 | .13 | .08 | .05 |
| MOS | .50 | .26 | .14 | .06 | .04 |
| PERCENT of Wet Forecasts | | | | | |
| LOCAL | .09 | .21 | .27 | .24 | .18 |
| MOS | .08 | .27 | .31 | .20 | .14 |

Table I

Secondly, in general, both MOS and WSFO Indianapolis significantly underforecasted in the LIKELY category (60 and 70 percent). Even though during June, July, and August the use of 60 and 70 percent POP's verified very well (Table 2). During the remainder of the year there is a disproportionate amount of WET forecasts issued by the WSFO at 60, 70, and 80 percent (Table 3). At 60 percent, there were actually 51 out of 68 wet forecasts (75 percent). At 70 percent, 40 out of 46 forecasts had measurable precipitation (87 percent). At 80 percent, 38 out of 43 forecasts were wet (88 percent).

Overall, probabilities issued by the WSFO in the summer season showed rather good reliability. Most of the time, probabilities were used appropriately. There is, however, a glaring irregularity at 40 percent. The Indianapolis office forecast a 40 percent were wet 22 out of 44 times (50 percent). Similarly, MOS issuance of 40 percent were wet 51 percent of the time (25 out of 49) (Table 2).

MOS has an affinity for 20 and 30 percent POP's. One third of the forecasts issued by MOS in June, July, and August are either a 20 or 30 percent. In a paper by George Maglaras, on the use of MOS guidance, he explains "the LFM mean RH dominates the POP equation to such a degree that it is very difficult to get a POP above 30 percent, unless the mean RH is above 70 percent. As a result, many convective situations are underforecast because the LFM mean RH is not above 70 percent, even if the mean RH is accurate."

Again, for the entire year, in comparison to the MOS guidance, forecasters at the WSFO issued considerably MORE forecasts of 60 percent or greater (Table 1). The local office issued 272 forecasts of 60 percent or greater, 215 of those received measurable precipitation (79 percent), while MOS issued only 215 forecasts, 171 were wet (80 percent). The local office performed well in significantly reducing the number of "slight chances" (20 and 30 percent) and issuing 44 more WET high POP's (60 to 100 percent). That's a pretty good job!

But could the forecasts have been even better? I believe so. Consider the current state of the forecast science in regard to these factors: automation due to AFOS and office personal computers has resulted in a faster delivery of information and an easier/quicker means to prepare, edit, and update a forecast; local analysis by means of mesoplots, SWIS, and local radar give a timely delivery of additional information; and the Central Region's concept of enhanced local forecasts allows for more creative and innovative forecast wording.

A potential flaw in this systematic process of formulating a forecast and attempting to improve on the MOS guidance, is the forecaster's concern for accountability. This is more widely known as verification skill score. An intimidating monster has been created that may inhibit skilled meteorologists from making bolder predictions at the cost of losing points in the verification game. It is a game that biases the forecaster to stay near guidance or go a hair closer to 50 percent than the MOS value.

JUNE - JULY - AUGUST

WSFO IND

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PROB | 00 | 2-5 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | |
| RAIN | 0 | 0 | 5 | 12 | 20 | 22 | 25 | 22 | 9 | 5 | 3 | 0 | |
| FCST | 93 | 64 | 102 | 76 | 64 | 44 | 47 | 37 | 13 | 6 | 3 | 0 | |
| R/F | 00 | 00 | 05 | 16 | 31 | 50 | 53 | 60 | 70 | 83 | 100 | 00 | PCT |

LFM MOS

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PROB | 00 | 2-5 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | |
| RAIN | 0 | 0 | 8 | 24 | 17 | 25 | 24 | 15 | 5 | 4 | 1 | 0 | |
| FCST | 61 | 77 | 101 | 106 | 76 | 49 | 43 | 23 | 8 | 4 | 1 | 0 | |
| R/F | 00 | 00 | 08 | 23 | 22 | 51 | 56 | 65 | 63 | 100 | 100 | 00 | PCT |

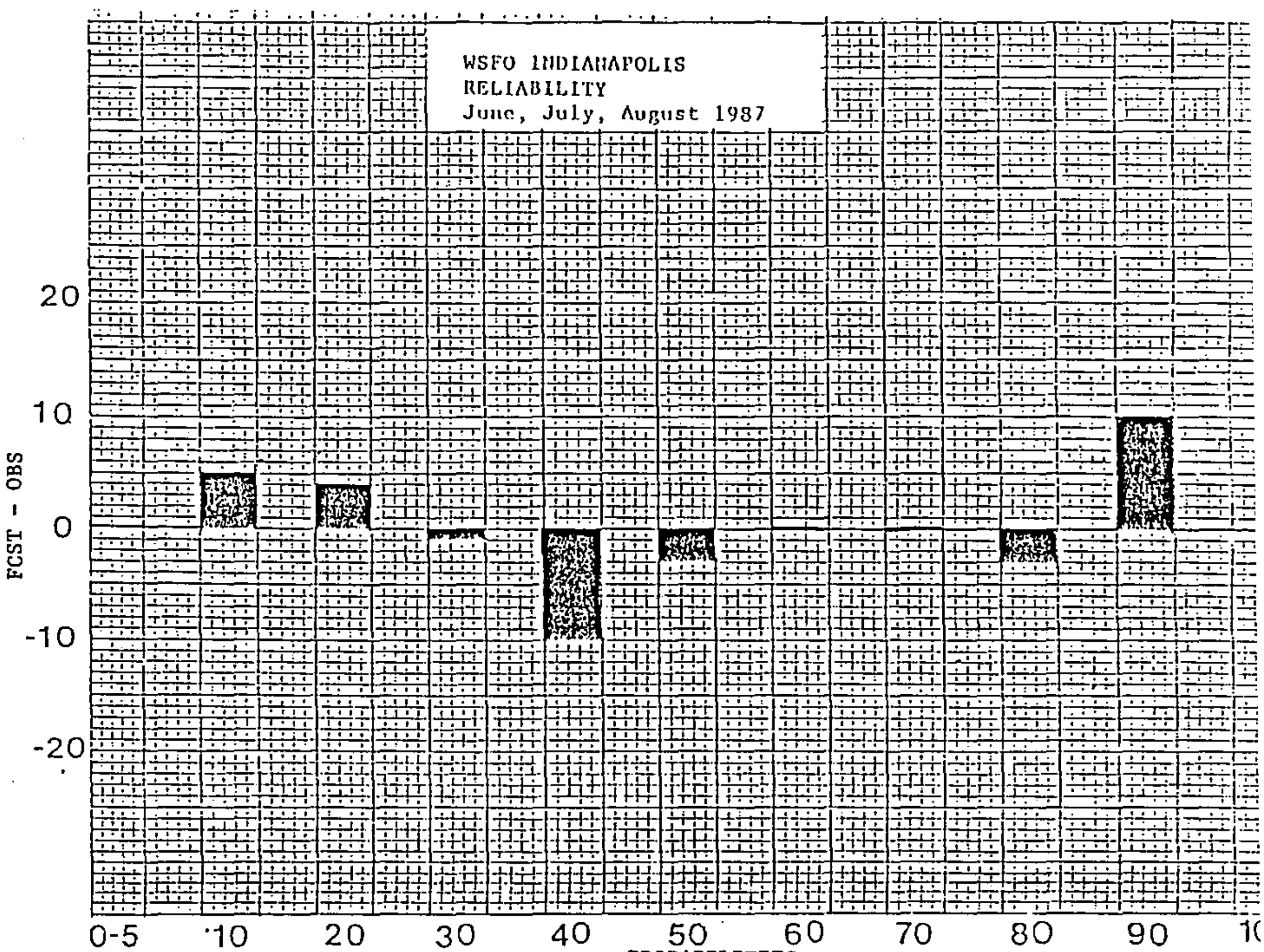


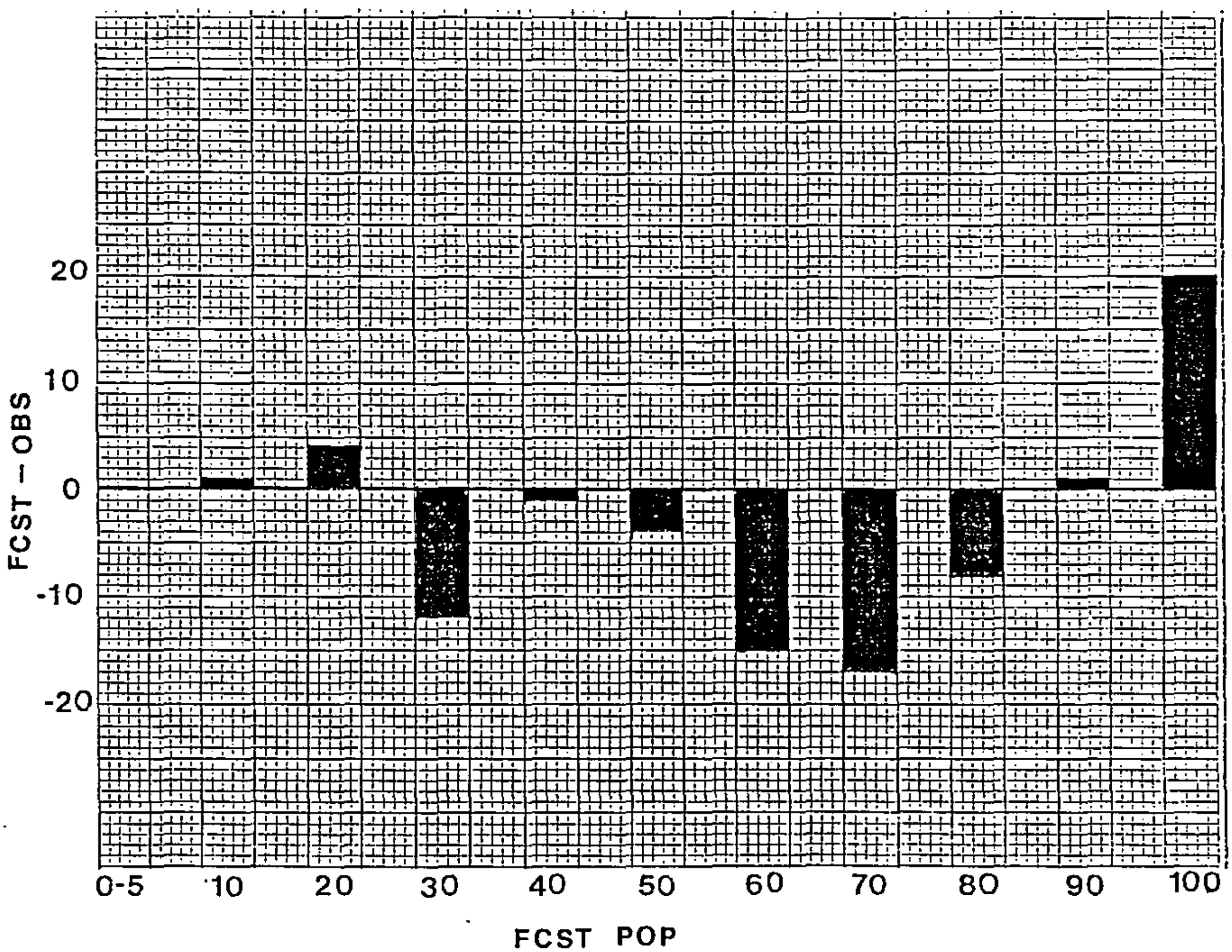

Table II

POP DISTRIBUTION EXCLUDING JUNE/JULY/AUGUST

March 1987 - February 1988

WSFO IND

| PROB | 00 | 2-5 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RAIN | 6 | 5 | 29 | 27 | 48 | 43 | 48 | 51 | 40 | 38 | 24 | 23 |
| FCST | 447 | 185 | 307 | 169 | 115 | 104 | 89 | 68 | 46 | 43 | 27 | 29 |
| R/F | .01 | .02 | .09 | .16 | .42 | .41 | .54 | .75 | .87 | .88 | .89 | .80 |




RELIABILITY excluding JUNE/JULY/AUGUST

Table III

Operational forecasters are well aware that once MOS breaks above 50 percent there is more to lose and less to gain by deviating towards higher POP values. The reason for this is that the Brier verification score is a result of squaring the error. If the forecaster truly believes the chances for wet weather are near 100 percent and if the guidance is 60 percent, the "safe forecast" is 70 percent (Table 4). A 50 percent forecast has even more potential gain.

Unfortunately, some of the creativity has been stifled on two other fronts: (1) in requiring the first period of the forecast to stand alone, and (2) 12 hour verification periods that end at 12Z and 00Z. The two, at times, jointly affect the wording of a late afternoon and evening precipitation event.

For example, a frontal boundary is expected to produce a line of thundershowers as it moves across the zone during the late afternoon and early evening. Confidence is high in the event but not as certain as to the timing and coverage of the rain. The forecaster might word the forecast something like this:

.Today...Partly cloudy with a 30 percent chance for later afternoon thundershowers, etc.
.Tonight...Partly cloudy with a 30 percent chance for evening thundershowers, etc.

An alternate wording that would eliminate the redundancy of the 30 percent would be:

.This morning through mid afternoon...partly cloudy. High in the middle 80s.
.Late this afternoon and early tonight...A 50 percent chance for thundershowers, etc.

Note here that the POP is raised because the time period is better fitted to cover the event most likely to occur between 1500 EST and 2000 EST.

Here is another possible example of wording for the event rather than locking into the standard verification times.

.This afternoon...warm and humid. Scattered thunderstorms developing after 2PM and ending before 9PM. Coverage of rain 30 percent.
.Overnight...muggy. (Thunderstorms are not mentioned again, yet 30 percent POP may be logged for overnight verification.)

BRIER SCORE (see text)

| PROBABILITY % | NO "RAIN" OBSERVED | "RAIN" OBSERVED |
|---|---|---|
| 0 | .00 | 1.00 |
| 2 | .0004 | .9604 |
| 5 | .0025 | .9025 |
| 10 | .01 | .81 |
| 20 | .04 | .64 |
| 30 | .09 | .49 |
| 40 | .16 | .36 |
| 50 | .25 | .25 |
| 60 | .36 | .16 |
| 70 | .49 | .09 |
| 80 | .64 | .04 |
| 90 | .81 | .01 |
| 100 | 1.00 | .00 |

TABLE IV

And still more:

.Tonight...Thunderstorms likely after midnight. Heavy rain possible, etc., chance for rain 70 percent.
.Wednesday and Wednesday night...Partly cloudy. A 30 percent chance for afternoon and evening thunderstorms. (Note here the POP is only mentioned once yet covers both periods.)

Similar wording can be applied to a variety of precipitation events. By bracketing events with specific times you can avoid the redundancy of reporting precipitation probabilities.

With a meteorological array of upgraded technology already in place and the NWS standing on the threshold of NEXRAD, profilers, and AWIPS challenges, this generation of meteorologists is challenged to issue more accurate forecasts. Skillful interpretation of weather parameters integrated with numerical models, SWIS data, local radar and surface reports can assist in communicating the forecast clearly and concisely. The goal is to emphasize the timing of precipitation events. Third and fourth period forecast wording can be trimmed to keep the forecast brief.

When situations present themselves that allow for innovativeness and enhancement, they must be communicated in specifics. Meteorologists must now begin to advance the science and accept the challenge of providing more detailed precipitation forecasts!

References

Curtis, J. C., and A. H. Murphy, 1985: Public interpretation and understanding of forecast terminology: Some results of a newspaper survey in Seattle, Washington. Bull. of Amer. Meteor. Soc., 66, 810-819.

Maglaras, G., 1987: How to use MOS guidance effectively, Part III. Central Region Technical Attachment 87-25, available from NWS Central Region, Scientific Services Division, Kansas City, MO.

# CENTRAL REGION APPLIED RESEARCH PAPER 99-3

# SOME REASONS FOR ABNORMALLY WET AND DRY MONTHS AT TOPEKA, KANSAS

Larry W. Schultz
National Weather Service Forecast Office
Topeka, Kansas

## 1. Introduction

Weather extremes are no stranger to the operational meteorologist. In fact, since "normal" weather is an average of the extremes, it is rare indeed for weather to actually be normal for any length of time.

Precipitation patterns are no exception. Extremes in precipitation can occur on a daily basis as well as monthly, yearly, etc. The purpose of this paper is to investigate the occurrence of monthly precipitation extremes at Topeka, Kansas, during the warm season, and to discover some of the possible causes.

## 2. Method

Twelve warm season months with abnormal precipitation at Topeka, Kansas, were selected for the study. The 12 months occurred between the years 1967 and 1980, and included six abnormally wet and six abnormally dry months. Only those months with less than 25 percent, or greater than 200 percent, of normal precipitation were considered. The 12 selected months were the only months during the period of study to meet these criteria.

The months selected, along with monthly precipitation totals and percent of normal precipitation, are shown in Table 1. Notice that the six dry months selected averaged only 17 percent of normal precipitation while the six wet months averaged 284 percent of normal. Two of the months (June, 1967 and September, 1973) recorded over 300 percent of normal precipitation while one month (August, 1971) received less than 10 percent of normal precipitation.

Mean monthly upper air data for the 12 months surveyed was taken from the NOAA publication "Climatic Data National Summary." Values of temperature, dew point and wind for the six wet months were averaged and placed in one group. Values of these parameters for the six dry months were averaged and placed in a second group. (It should be noted that winds for both groups were averaged in the following manner: the directions were averaged by azimuth, then the speeds were averaged by knots.)

Table 1

| Wet Months | | | Dry Months | | |
|---|---|---|---|---|---|
| Month | Pcpn | % of nor | Month | Pcpn | % of nor |
| Jun 1967 | 15.20 | 312% | Aug 1970 | 0.83 | 21% |
| Jul 1968 | 10.17 | 262% | Aug 1971 | 0.26 | 7% |
| Jul 1973 | 10.16 | 262% | Jul 1975 | 0.68 | 18% |
| Sep 1973 | 12.71 | 361% | Aug 1976 | 0.86 | 22% |
| Jun 1977 | 10.91 | 224% | Jun 1980 | 0.56 | 11% |
| Aug 1977 | 11.18 | 280% | Jul 1980 | 0.87 | 22% |
| Mean | | 284% | Mean | | 17% |

Once the data had been averaged, RAOB's were then plotted for both groups. These mean soundings are shown in Figure 1. Figure 1a shows a comparison of both soundings, while Figure 1b shows the thermodynamic data for each sounding individually.

## 3. Discussion

An inspection of the thermodynamic data (Figure 1b) shows that the various stability indices were nearly identical in both the wet and dry months. What moisture differences did exist were apparent only above 700 mb (Figure 1a) where the atmosphere was slightly drier in the dry months. But this difference was not sufficient to effect a major change in either the precipitable water values or the K-index (Figure 1b). Perhaps the biggest difference occurred in the lower layers below 700 mb where temperatures in the dry months were some two or three degrees warmer than in wet months.

Mean wind speeds and directions for the six wet months were plotted and compared with the mean speeds and directions for the six dry months. These plots are shown in Figure 2.

In both cases the maximum speeds occurred near the 200 mb level. The high level winds are stronger in wet months than the dry ones. This seems to imply the existence of a jet stream and baroclinic zone near the area, although the actual wind field was quite weak for both cases. In lower layers of the atmosphere (below about 800 mb) speeds were nearly the same in both wet and dry months, although the pattern in dry months is more jet-like in nature.

Existence of jet streams in both the lower and upper layers of the atmosphere has long been recognized as necessary for the production of severe convective weather (Beebe and Bates, 1955; McNulty, 1978). Although

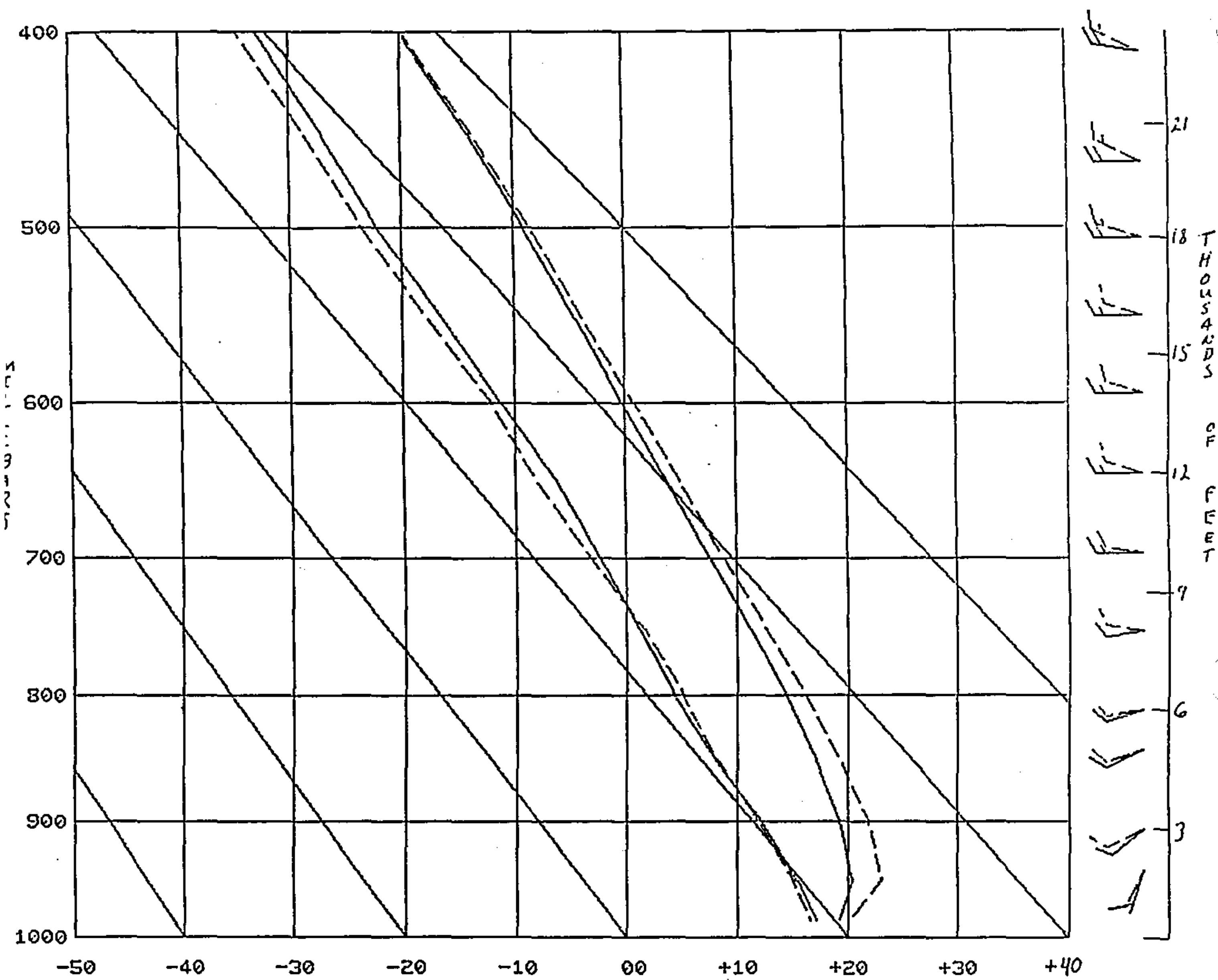



FIGURE 1A. MEAN ATMOSPHERIC SOUNDINGS TO 400 MILLIBARS FOR WET AND DRY MONTHS AT TOPEKA, KANSAS. SOLID IS FOR WET MONTHS, DASHED IS FOR DRY MONTHS.

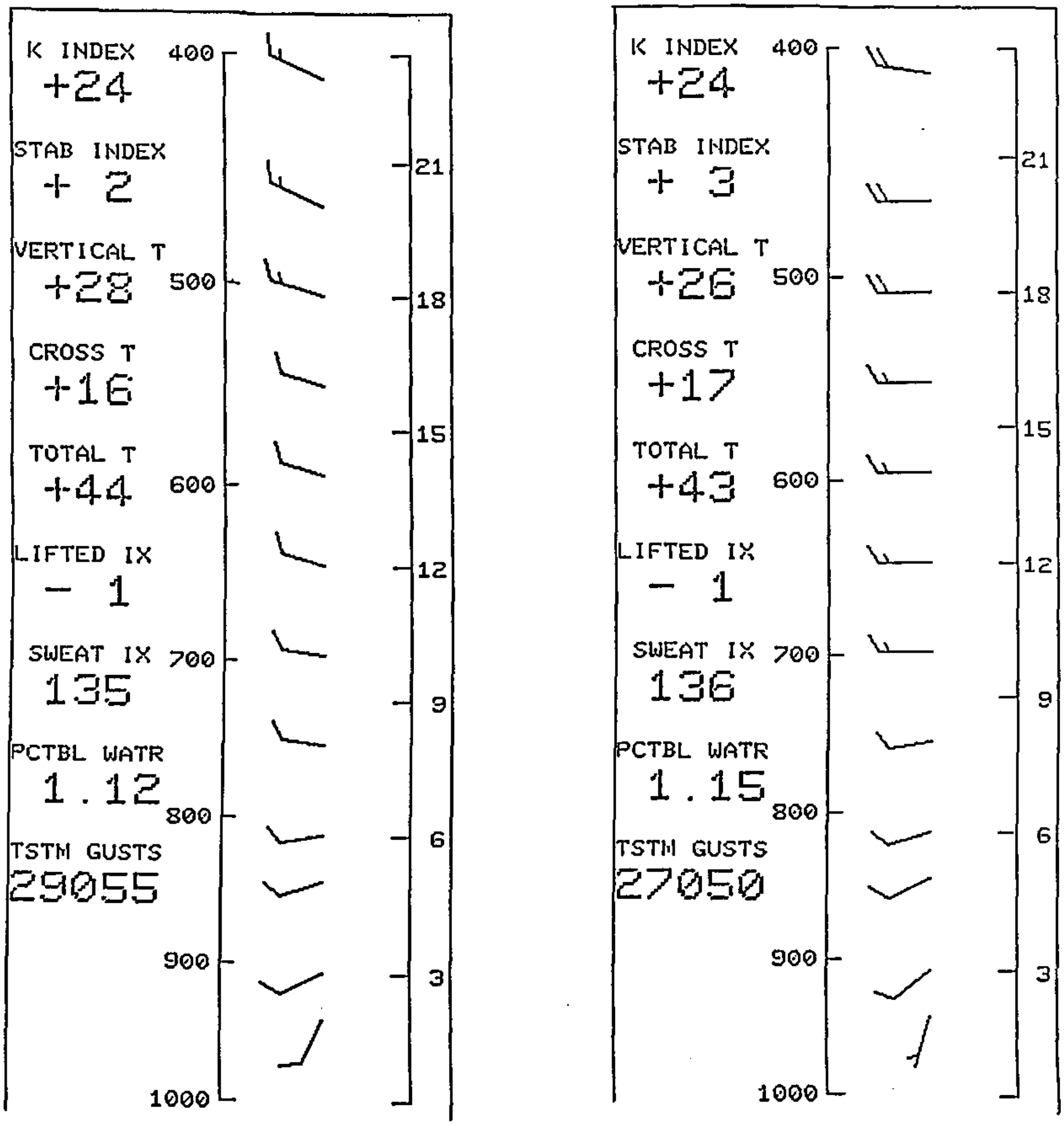
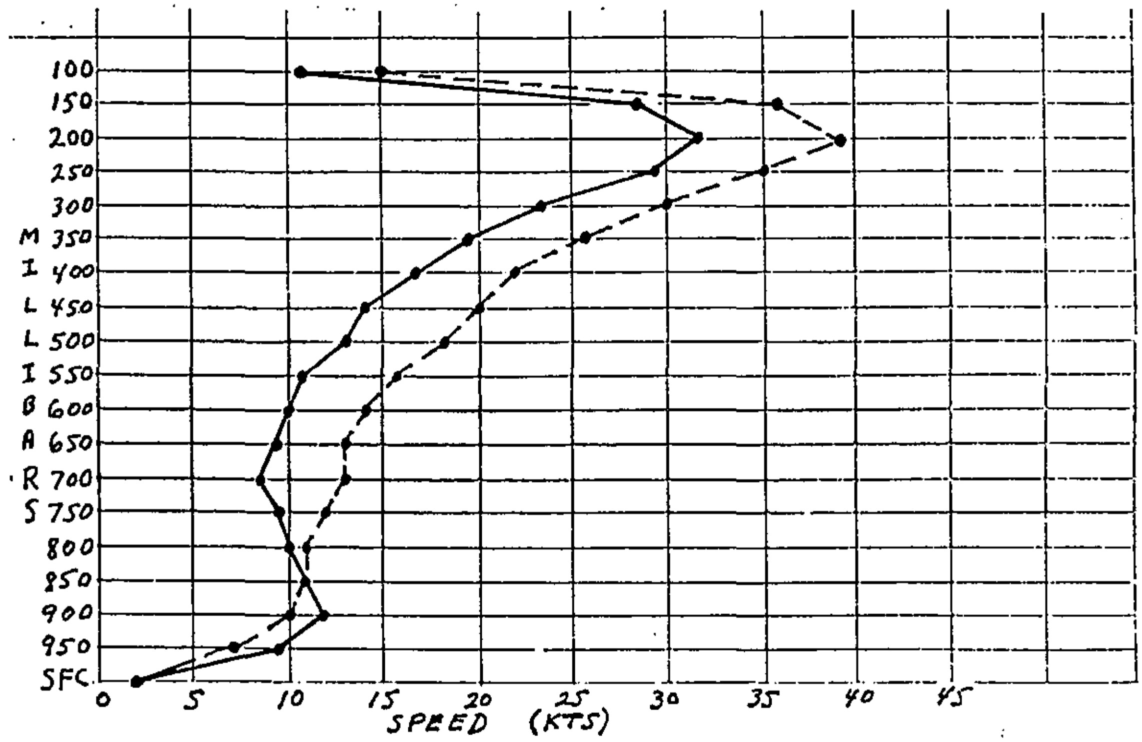



FIGURE 18. MEAN THERMODYNAMIC DATA FOR DRY (LEFT) AND WET (RIGHT) MONTHS.



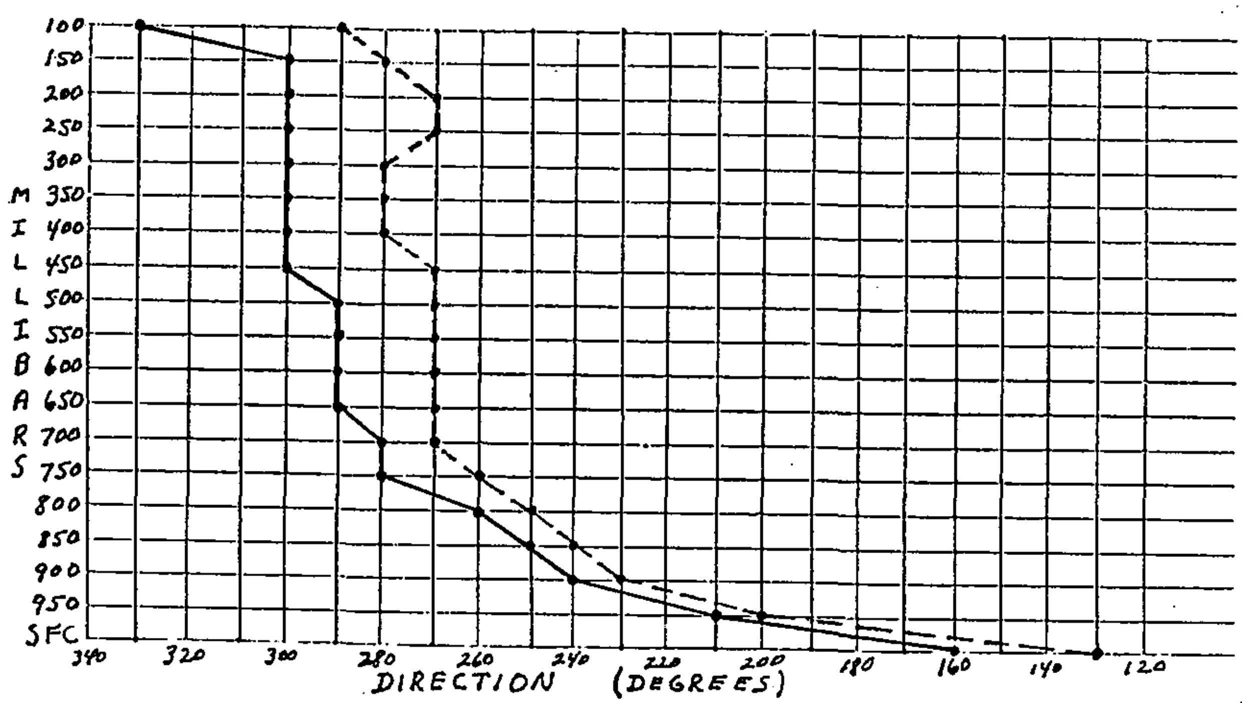




FIGURE 2. MEAN WIND PROFILES OF SPEED (TOP) AND DIRECTION (BOTTOM) FOR THE 6 DRY (SOLID) AND 6 WET (DASHED) MONTHS OF STUDY.

severe weather does not necessarily imply heavy rain, the fact that wet months clearly exhibited the existence of a stronger upper level wind field indicates that severe weather and heavy rainfall are often associated with each other. On the other hand, a low level jet was not discernible in the wet months, contrary to the conditions that occur during severe weather production.

Both wet and dry month cases had minor variations in wind direction from each other in the lower layers of the atmosphere. The largest directional difference occurs in middle and upper layers of the atmosphere above 650 mb. Above this level winds are from a westerly direction in wet months, and from the northwest in dry months -- a difference of some 20 to 40 degrees.

The upper level northwesterlies in the dry months would imply the existence of an anticyclone to the west of the region. Hence, Topeka would be situated downstream from the mean ridge position. Since upper level convergence and atmospheric subsidence is normally present downstream from the mean ridge position, the high level wind and monthly precipitation patterns are entirely consistent with each other.

On the other hand, wet month westerly winds would imply that the ridge position is in the Topeka vicinity with southwesterly winds, high level divergence, and atmospheric upward motion located just to the west of the region. Upper flow patterns could then advect thunderstorms eastward over the Topeka area from this genesis region just to the west.

Mean wind directions and speeds for lower and upper levels of the atmosphere for both cases are shown in Table 2. (Because the mean surface winds were very light, the 950 mb level was used as the bottom limit of the low level wind layer.) From Table 2 it can be seen that more directional shear is present in the dry months while more speed shear occurs in wet months. Large wind shears tend to shear off the convective cloud tops before they can reach the rain-producing thunderstorm stage. The results of this study seem to imply that directional shear is a more important inhibitor of rain-producing thunderstorms than speed shear.

Table 2

| | Mean Wind | | Shear | |
|---|---|---|---|---|
| | (950-750 mb) | (300-100 mb) | Directional | Speed |
| Dry | 24810 | 30625 | 58 deg | 15 kts |
| Wet | 23610 | 27932 | 43 deg | 22 kts |

The upper air wind patterns (700 through 200 mb) of the wet months more closely resembled the mean conditions associated with individual frontal and mesohigh type heavy rain and flash flood events as described by Maddox et al (1979). (See, for example, their Tables 2 and 3, and Figures 8c and 10c.)

Mean temperatures (surface through 500 mb) in the wet months are similar to mean conditions for frontal and mesohigh events.

The daily weather map series was examined for each of the 12 months in question to determine the number of identifiable frontal boundaries present within 50 miles of Topeka. (Although surface troughs, outflow boundaries, etc., also produce warm season precipitation, only frontal boundaries were consistently available from the daily weather map series.)

Table 3 summarizes the "frontal availability" for the wet and dry month cases. From the table it may be seen that in wet months frontal activity is about 25 percent greater than during dry months.

Table 3
Fronts/Frontal Passages

| | Wet Months | Dry Months |
|---|---|---|
| # of days available | 183 | 185 |
| # of fronts | 63 | 50 |
| % of possible | 34% | 27% |

## 4. Summary and Conclusions

Weather patterns associated with six abnormally wet and dry months at Topeka, Kansas, during the warm season were examined. From these data the following conclusions have been made:

a. Fronts and frontal passages are important as precipitation producers.

b. Upper level winds tend to blow from the west in wet months and from the northwest in dry months. The former implies a ridge line lies over the region with high level divergence (and upward motion) just to the west of the threat area. The latter implies the ridge line is well to the west of the region with upper level convergence (and atmospheric subsidence) present over the threat region.

c. Directional wind shear is less in wet months and greater in dry months. Large wind shears tend to shear off the tops of the deep convective clouds before they can develop into rain-producing thunderstorms. Directional shear seems to be more important in this regard than speed shear.

d. Upper level winds are stronger in wet months which implies the existence of an upper jet and baroclinic zone nearby.

e. Since air mass thermodynamic properties are essentially the same in both wet and dry months, the presence or lack of a triggering mechanism seems to be the determining factor in the occurrence or non-occurrence of warm season precipitation.

## 5. Acknowledgments

The author wishes to thank Dr. Richard P. McNulty (Deputy Meteorologist in Charge at the National Weather Service Forecast Office in Topeka) for helpful comments and suggestions, and for reviewing the manuscript.

## 6. References

Beebe, R. G., and F. C. Bates, 1955: A Mechanism for assisting in the release of convective instability. Mon. Wea. Rev., 83, 1-10.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso-scale aspects of flash flood events. Bull. Amer. Meteor. Soc., 60, 115-123.

McNulty, R. P., 1978: On upper tropospheric kinematics and severe weather occurrence. Mon. Wea. Rev., 106, 662-672.

CRH SSD
CRARP 99-4

# CENTRAL REGION APPLIED RESEARCH PAPER 99-4

# INVESTIGATION OF SIGNIFICANT TEMPERATURE CHANGES ACROSS WYOMING

Hugh G. McRandal, Jr.[1]
National Weather Service Forecast Office
Cheyenne, Wyoming

## 1. Introduction

A Significant Temperature Change (STC) is defined to be a change greater than $10^{o}F$ between successive maximum or minimum temperatures. An analysis of these STC events across Wyoming shows that they are extremely variable both spatially and temporally. This paper will discuss the findings of research into STC at the five sites across Wyoming. A statistical analysis on the maximum and minimum temperatures is initially presented. Next, an analysis looking at the spatial and temporal and length of occurrence is given. Finally, the analysis of STC's is used to derive composite 500 mb analysis associated with predominate STC events during the warm and cool seasons.

## 2. Stations Used

Wyoming is a state of differing climates and topographic features. The climate is predominantly determined by its latitude, altitude, and the local topography (Fig. 1). The physiographic features act in concert with migrating synoptic weather systems to control the low-level air flow patterns and the extent of temperature, precipitation, humidity, and other weather conditions (Martner, 1987).

Most of Wyoming can be classified as a "steppe" climate (Fig. 2) typical of semi-arid grasslands and prairies (Martin, 1987). To study STC, data from major meteorological stations were analyzed for the period 1980 to 1985. Five stations were chosen: Casper, Cheyenne, Lander, Sheridan and Rock Springs.

Casper is located in the central portion of Wyoming in the valley of the North Platte River. The elevation of Casper is 5,338 feet above mean sea level (MSL). The terrain around Casper is predominantly rolling and hilly, but with considerable flat prairie land in all directions except the south where Casper Mountain rises 3,500 feet above the valley.

---

[1] Mr. McRandal is now affiliated with the National Meteorological Center's Monitoring and Aviation Branch.

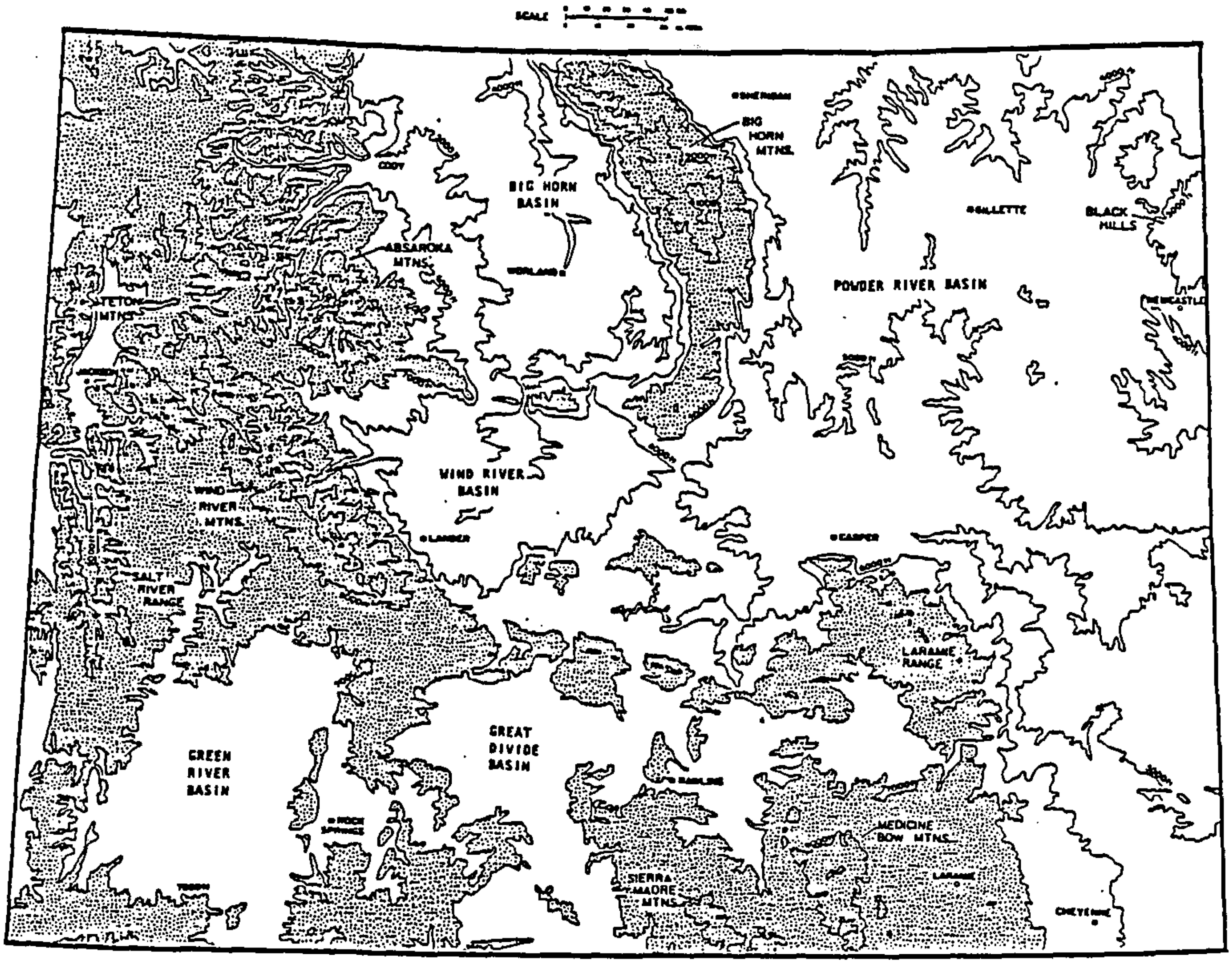



Fig. 1. Wyoming Topography(Reprinted from Wyoming Climate Atlas, Martner, 1987). Regions above 7,000 feetMSL were shaded.

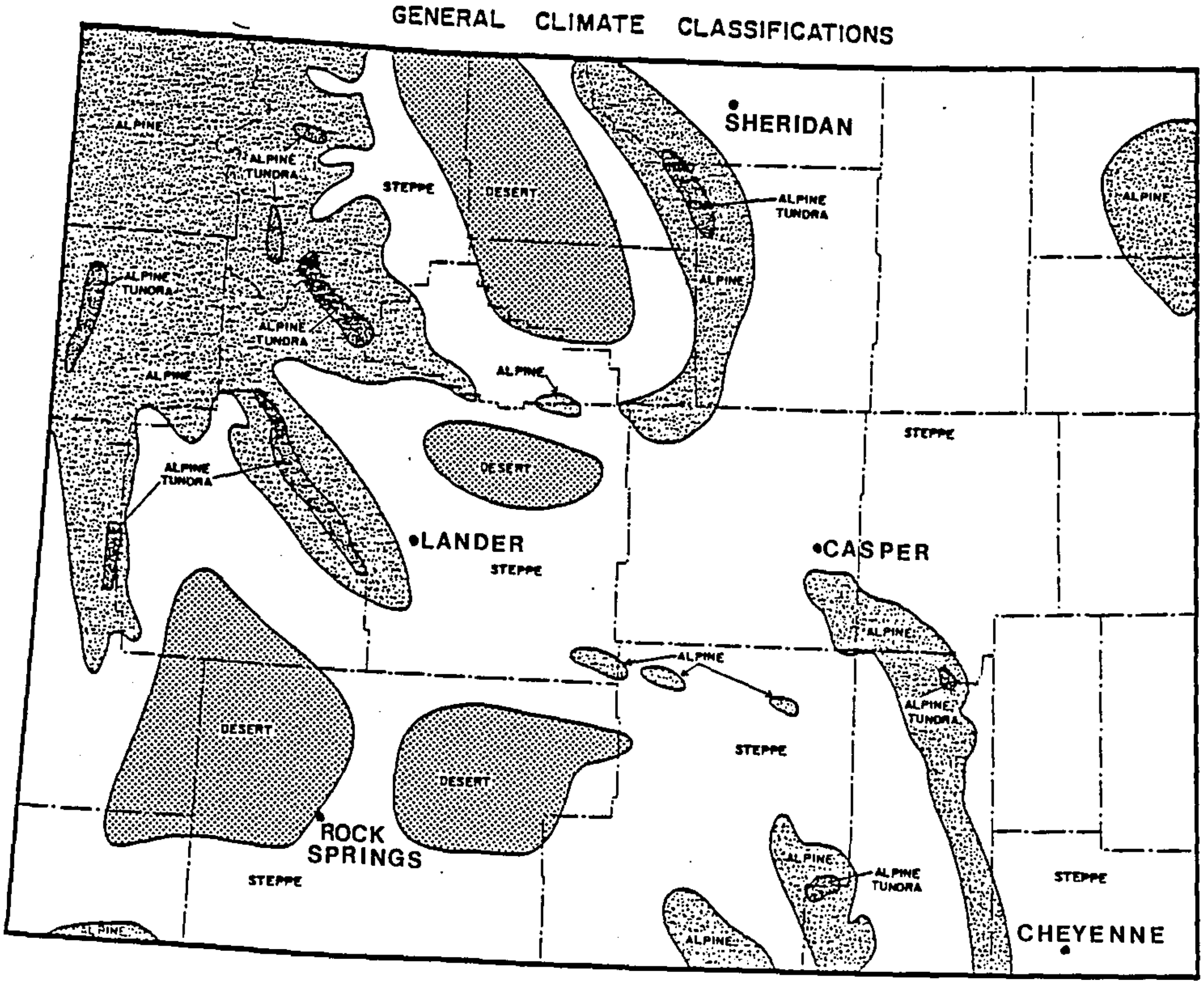



Fig. 2. Climatic Classification(Reprinted from Wyoming Climate Atlas, Martner, 1987).

Cheyenne is located in the extreme southeast corner of Wyoming at an elevation of 6,126 feet (MSL). The terrain west of the city rises gradually to mountains near 9,000 feet (MSL) in elevation about 40 miles west. This group of mountains, the Laramie Mountains, produces a pronounced downslope effect when northwest, west, or southwest winds are occurring. Cheyenne is physically built on a broad ridge between the North Platte and South Platte Rivers. Therefore, winds from an east, north, or south direction produce a marked upslope effect.

Lander is situated in west central Wyoming along the Popo Agie River, east of the Wind River Mountains. The elevation of Lander is 5,563 feet (MSL). The airport weather station is located on a mesa about a mile and a half south- southeast and 200 feet above the city. With the way Lander is situated, winds from all directions except northeast are downslope. Steep temperature inversions are the rule during winter nights and early mornings and temperature differences can be quite large between the mesa and the city which lies on the valley floor. This is particularly true on calm nights with snow on the ground.

Sheridan is positioned in north central Wyoming just adjacent to the Big Horn Mountains. Since the Big Horns are west of the city, westerly winds are downslope, while winds from an easterly and northeasterly direction are upslope. The elevation at the airport site is 3,964 feet (MSL).

Rock Springs is located in southwest Wyoming. The observing site for Rock Springs is Sweetwater County Airport located on a mesa at 6,741 feet (MSL) (about 500 feet above the city). A number of high ridges, buttes and plateaus surround the airport.

## 3. Statistical Examination

### A. Coefficient of Variation Analysis

Statistical analysis of monthly mean maximum and minimum temperatures for the period 1980 to 1985 was performed on the five stations. The standard deviation was used to differentiate between normal and abnormal temperatures. Over 90 percent of the mean monthly maximum and minimum temperatures were within one standard deviation of the 30 year mean, and all (100 percent) of them were less than two standard deviations from the 30 year mean. This establishes that the period from 1980 to 1985 was "normal" (Pieke and Waage, 1987).

Often, a comparison of standard deviations (SD) is used to show how much spread is present between numerous data sets. However, this can be deceiving if the SD depends on the value of the initial data sets and their associated means. The dimensionless coefficient of variation (CV=SD/Mean)

(Tout, 1987) accounts for this and is used to ascertain the variability of the mean maximum and minimum temperatures between 1980 to 1985 for the five observing stations. Large values of CV indicate large variability.

For the warm season (April through September), Cheyenne's minimum temperature had the lowest CV. It was only 0.062. Rock Springs' warm season minimum CV was only 0.063. In contrast, for the cool seasons (October through March), Sheridan showed the most variability with CV values of 0.157 and 0.472 for the maxima and minima, respectively.

This analysis indicates that both Cheyenne and Rock Springs had little variability during the warm seasons of 1980 to 1985, while Sheridan exhibited marked variability during the cool seasons of those years. This temporal analysis implies that during the cool season Sheridan may have a greater incident of STC conditions than the other stations. The analysis for the warm season indicates that Cheyenne and Rock Spring may have the higher occurrence of STC events during this season for the maxima and minima, respectively.

An AFOS computer program was written to analyze all the maximum and minimum temperatures from the five stations between 1980-1985. Basically, this program printed out all STC events for the five stations during the given period. The results from this program are plotted in Figures 3 and 4. Additionally, meteorological seasons, as defined by the NWS national verification program, divide the events into warm and cool seasons. Over 400 STC days for the warm season and over 200 days for the cool season were found.

B. Spatial Variation of STC

How much does the separation between the stations affect the STC occurrences across Wyoming? To test this, a Spearman's rank correlation coefficient examination was performed on the data. By this test, the data were examined for a common dependence on similar synoptic conditions. A perfect relationship (Rs=1) indicates complete agreement in order of rank.

Warm season maximum STC occurrences at Cheyenne were ranked against the STC occurrences of the other stations, while ones at Rock Springs were ranked against the other stations for the minima. The coefficients of STC for the maxima ranged from 0.92 to 0.98. The lowest correlation was the Cheyenne and Rock Springs pair while the highest one was between Cheyenne and Casper. The warm season minimum values showed a much smaller range from 0.97 to 0.98.

For the cool season Sheridan was ranked against the other four stations. The results showed much more variance. The maximum temperature STC values varied from 0.92 for the Sheridan and Rock Springs pair to 0.89 for the Sheridan and Casper pair. The coefficients for the minimum temperature STC ranged from 0.57 between Sheridan and Cheyenne to 0.93 for the Sheridan and Casper pair.

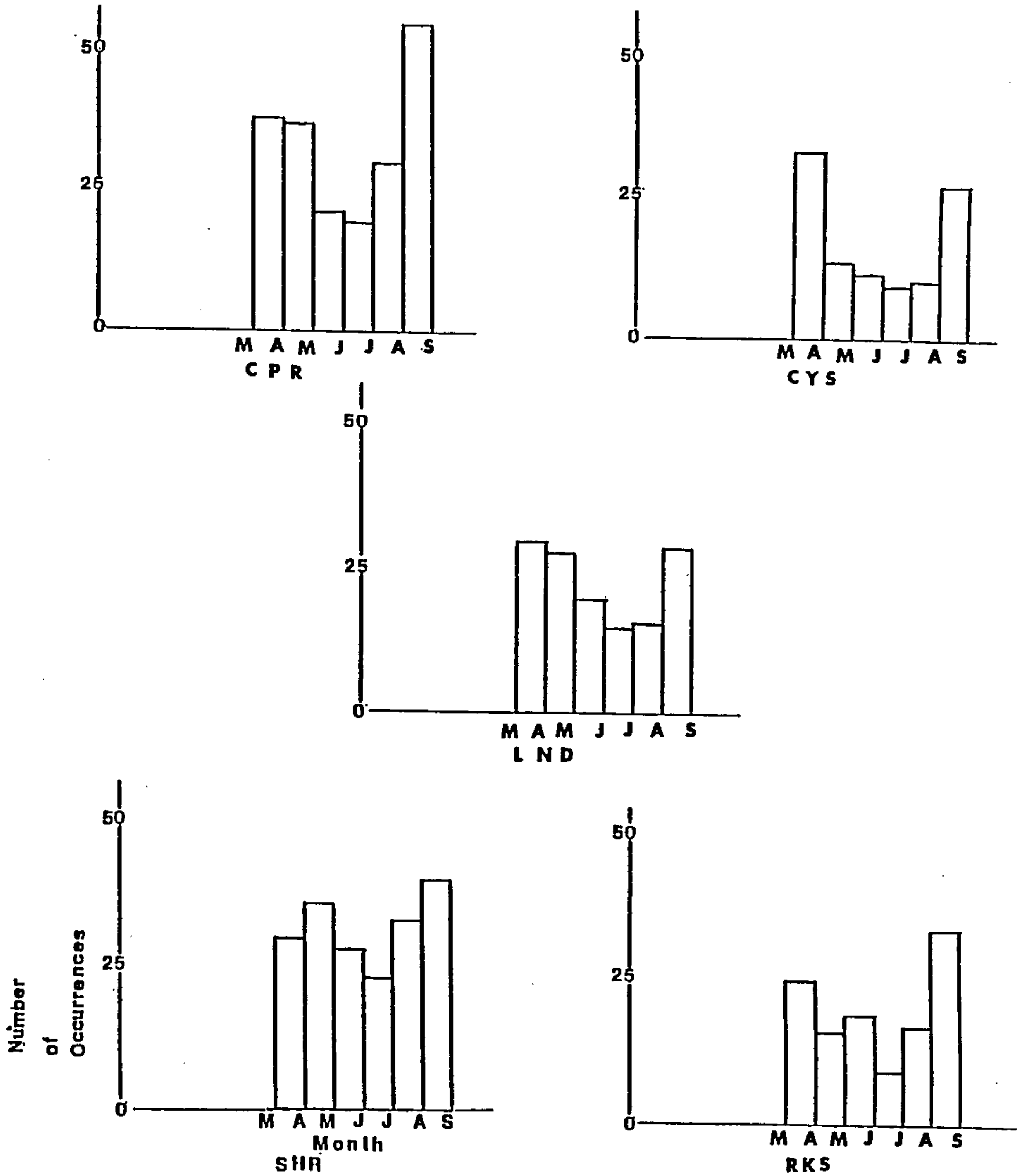



Fig. 3(a). Warm season maximum STC occurrences from 1980-1985.

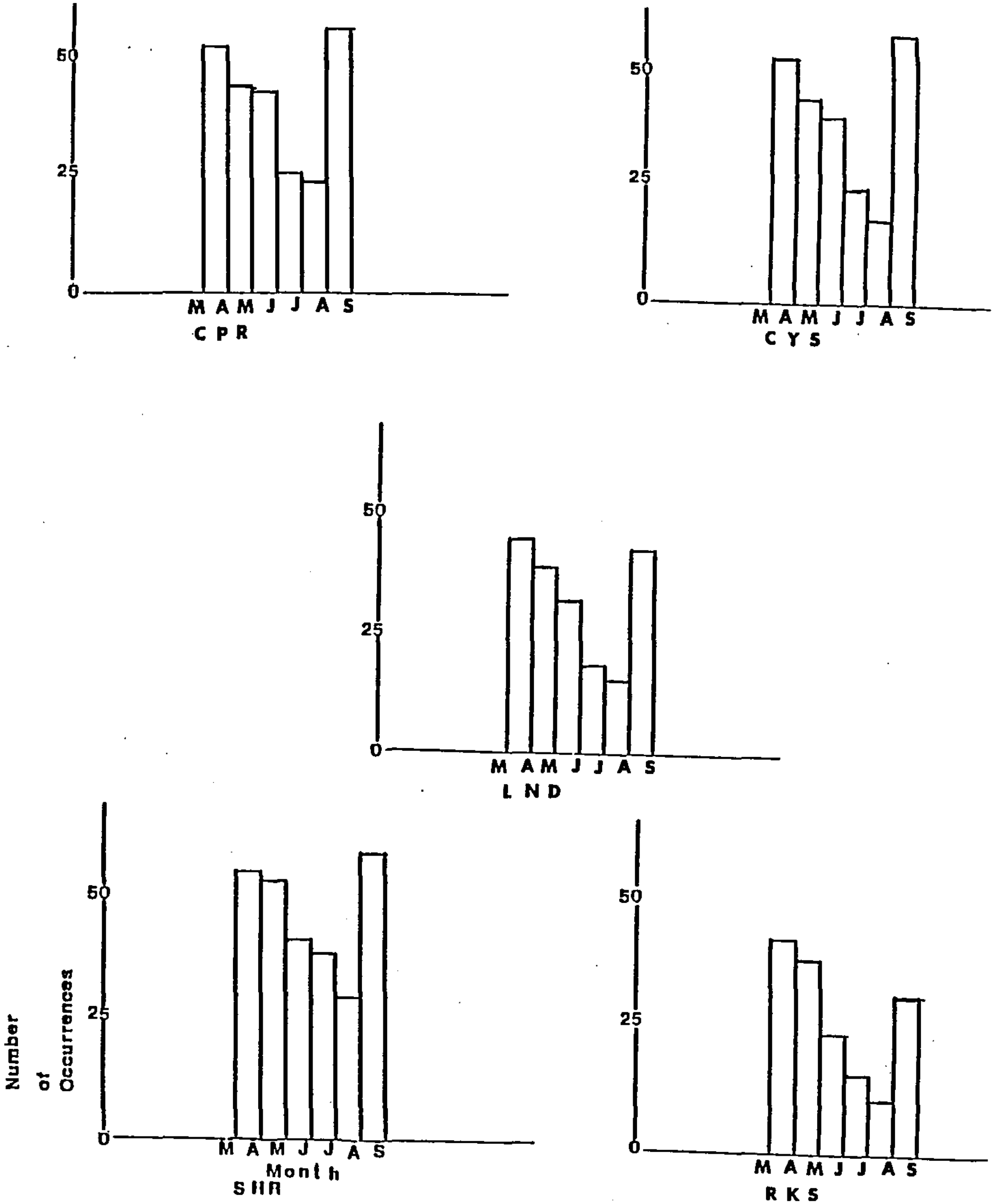



Fig. 3(b). Warm season minimum STC occurrences from 1980-1985.

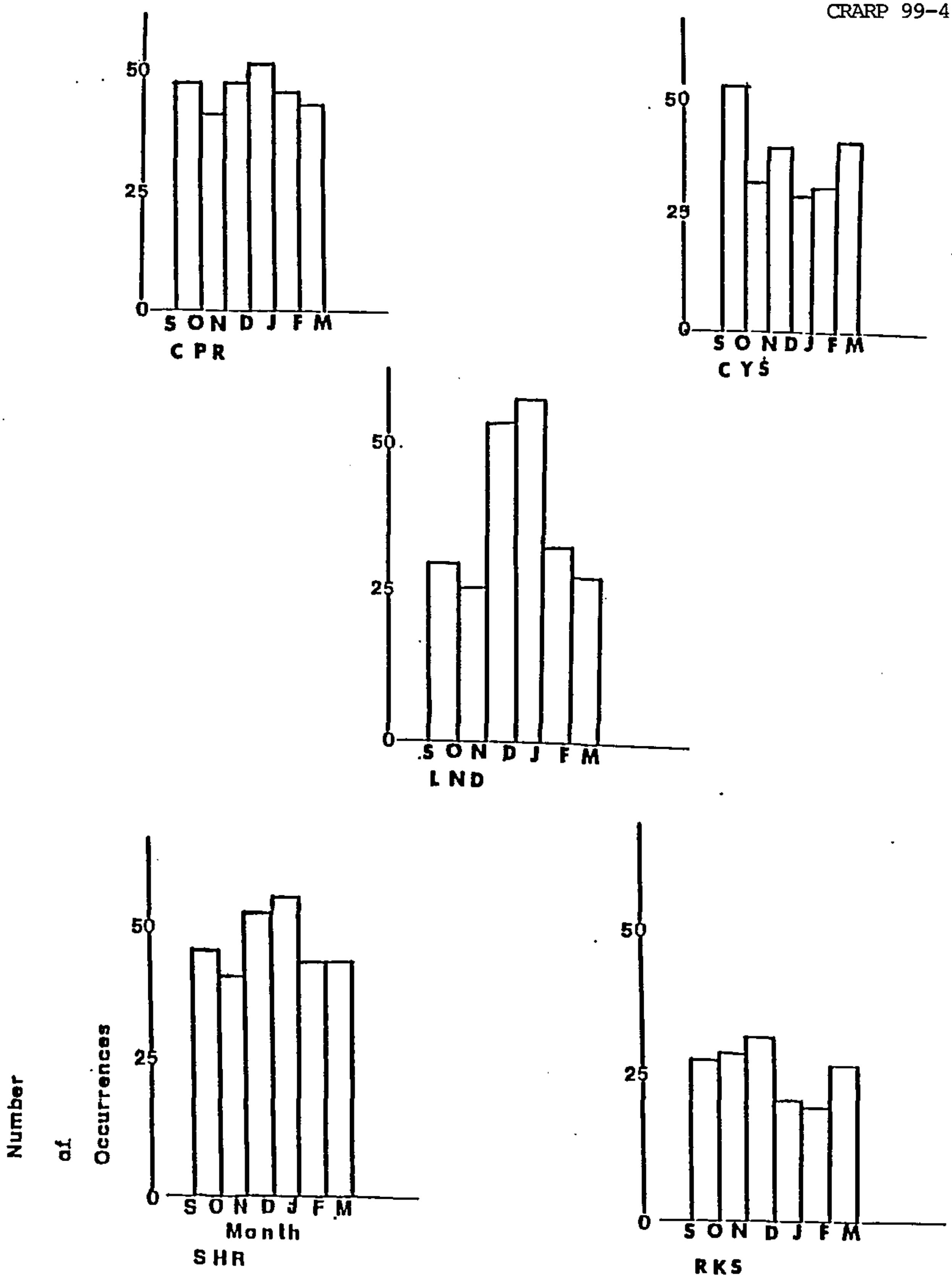



Fig. 4(a). Cool season maximum STC occurrences from 1980-1985.

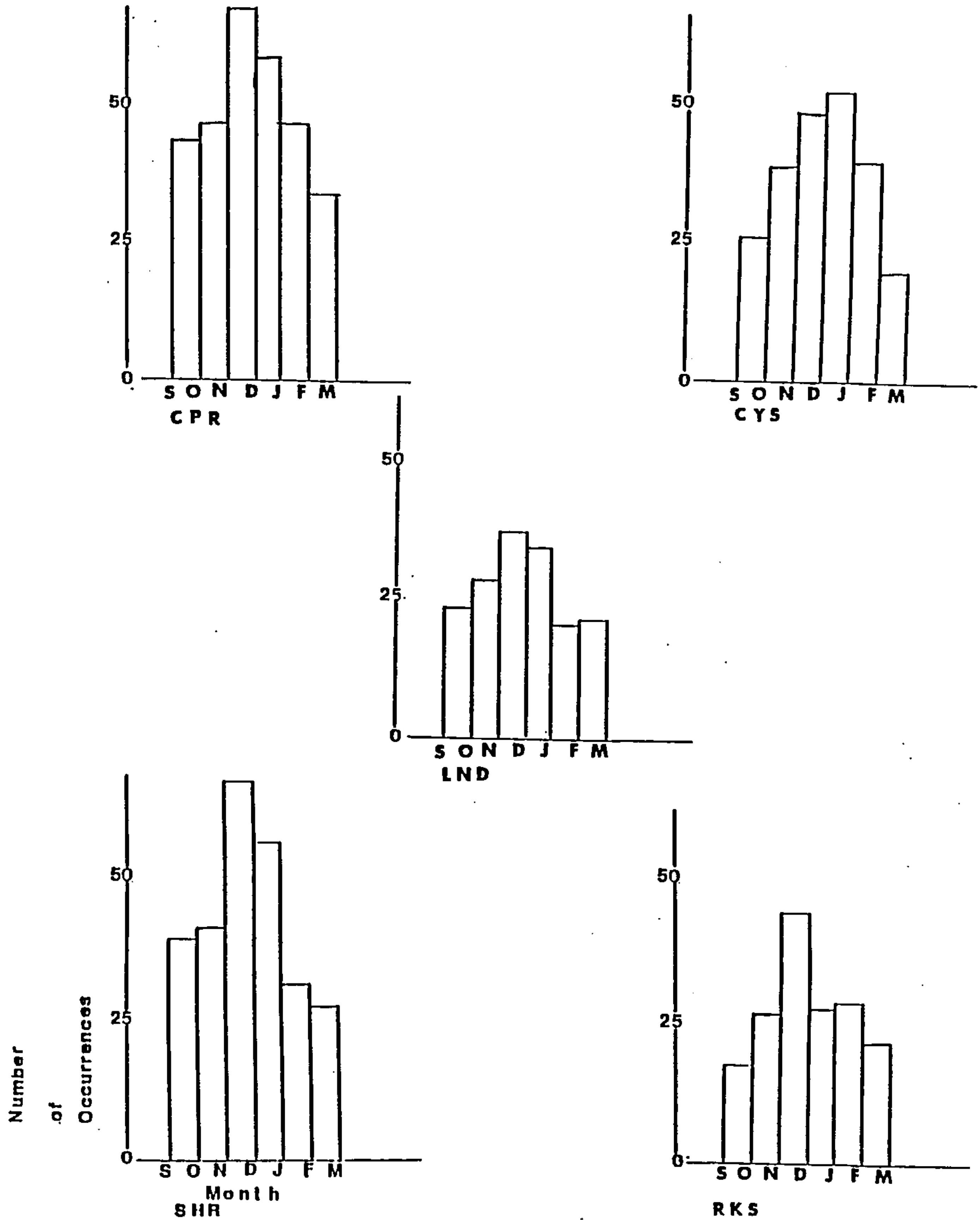



Fig. 4(b). Cool season minimum STC occurrences from 1980-1985.

Thus, spatial separation has a weak effect during warm season STC events. Spatial separation has a greater effect in the cool season STC occurrences, particularly those with minimum temperatures. Sheridan and Cheyenne have distinct cool season regimes for the STC minima occurrences.

C. Warm Season Frequency Distributions

The warm season STC events (Fig. 3) show a parabolic-like distribution between April and September. A distinct minimum in STC occurrences was detected during July and August with the largest number of STC's being mainly in April and September. The warm season maximum temperature data (Fig. 3a) showed that both Cheyenne and Rock Springs had markedly fewer STC occurrences than the other stations. The warm season minimum STC's (Fig. 3b) were, on average, more frequent than the maxima. The lack of occurrences during July and August is linked to the invasion of Pacific weather systems while Arctic ones weaken and retreat. Both April and September are periods of rapid change. April features variations in the westerlies and in the persistent high pressure over southern Canada. September is usually marked by periodic collapses of the deep tropical flow of summer, and its replacement by anticyclonic regimes accompanied by a rapid strengthening of the westerlies (Griffiths, 1976).

The average monthly number of STC days during the warm season for maxima ranged from five days in July to ten days in April and September. The average monthly number of STC days for minima ranged from three days in July to seven days in both April and September.

D. Cool Season Frequency Distributions

The cool season (Fig. 4) shows a different arrangement in the occurrences of maximum and minimum temperature STC's. December and January have, on the average, the highest occurrence of STC days. Looking at the maximum temperature STC events (Fig. 4a) shows that Rock Springs has less than the other stations. Except for the distinct peak observed in December and January, the variability across the cool season months was not very great. The minimum temperature STC events (Fig. 4b) show that Lander, on the average, has the fewest occurrences. The STC events for minimum temperature showed greater variability than the maximum temperature ones.

In the cool season, Wyoming is typically influenced by a strong zonal current which crosses the Pacific and enters the West Coast at about 40°N. This zonal flow is associated with a strong baroclinic zone and accompanying migratory surface fronts (Griffiths, 1976). December and January are about the middle of the cool season when snow is on the ground. This, combined with the migratory fronts, produces the high incidence of STC events.

The average monthly number of STC days during the cool season for maxima ranged from seven days in February, March, and November to nine days in January and December. While the average monthly number of STC days for minimum temperatures varied from five days in March to 11 days in December.

E. Classification of STC's According to Their Duration

In order to study sequences of STC's, the 400 warm season cases and 200 cool season ones were categorized as to whether they occurred singly or in a sequence of two days, three days, four days, or more than five days. In other words, we were studying how long the STC event lasted.

The results for the warm season are shown in Figure 5. The primary peak for both the maxima and minima was the two-day length with 55 percent of the maxima and 65 percent of the minima warm season occurrences lasting two days. There was also a secondary peak at a three-day length involving 21 percent and 20 percent of the maxima and minima, respectively.

Figure 6 shows the length distribution of STC events for the maximum and minimum temperatures for the cool season. The primary length is one-day for both maxima (39 percent) and minima (40 percent). Secondary peaks were for three-day lengths for maxima (27 percent) and two-day length for minimum (32 percent).

4. Fitting Synoptic Patterns to the Statistics

We have observed that by categorizing the warm and cool season STC values according to duration, that a preferred two-day duration appears for the warm season and a one-day length for the cool season.

With these two distinct statistical periods for the warm and cold season, we looked for predominant synoptic patterns that account for these distinct lengths? For this, 81 warm season cases and 78 cool season ones were examined. The cases were picked so that few of them overlapped.

A. Warm Season

Figure 7 shows a subjective composite 500 mb analysis before the start of a two-day long warm season STC event over Wyoming. Remember, most of the warm season STC cases are partitioned between April and September.

Essentially, the 500 mb pattern consists of an upper level ridge positioned east of Wyoming with a fairly strong short wave trough (and an associated cold front) approaching from the Pacific Northwest. By the end of day two this upper level trough and associated cold front has moved through Wyoming. As this happens high pressure, originally centered over southern Canada, spreads over Wyoming.

Typically, this 500 mb pattern produces strong warm advection combined with good downslope flow over Wyoming on day one. By day two, the Pacific

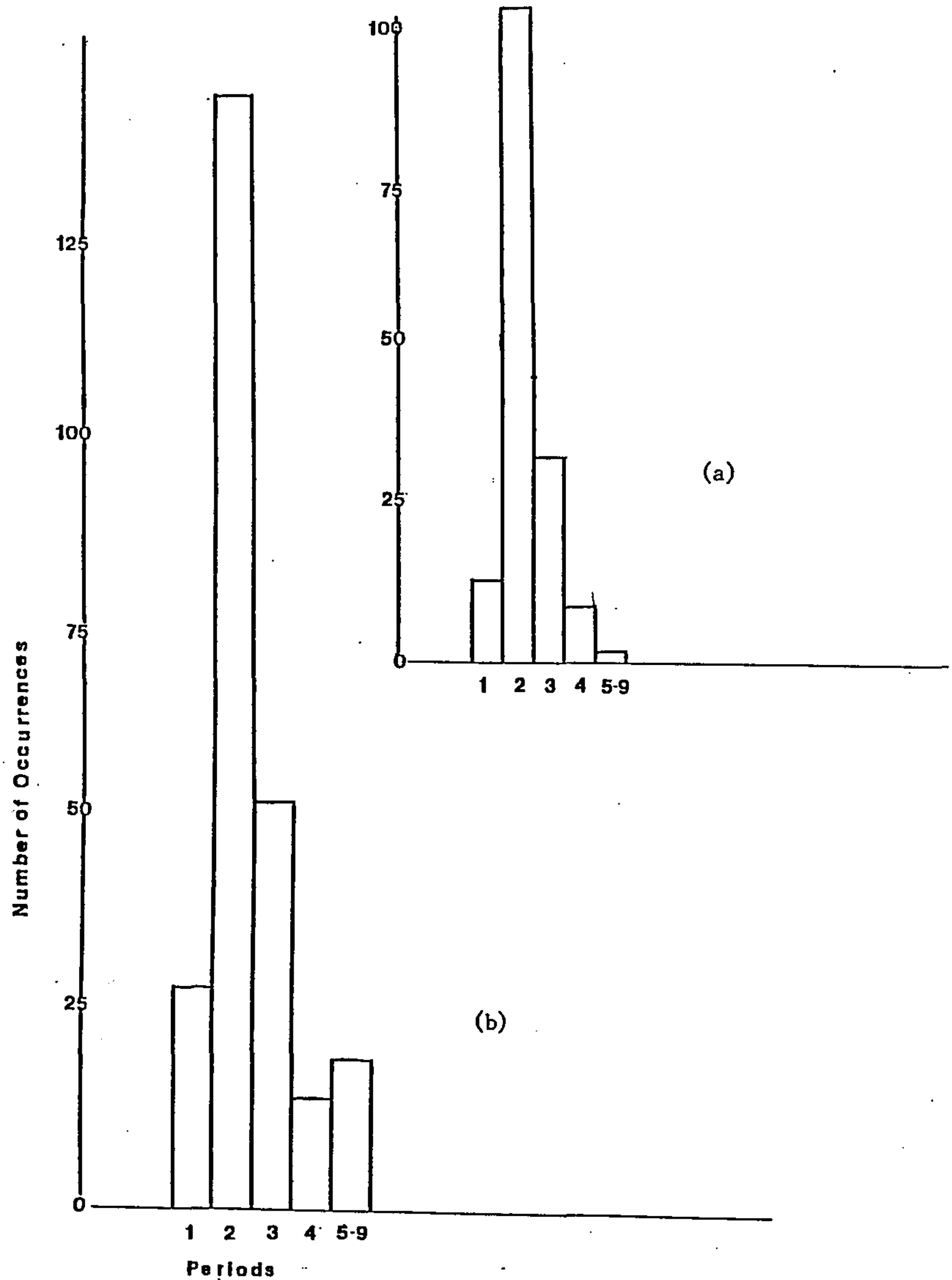



Fig. 5. Warm season time periods 1980-1985 (a) minimum temperature STC, (b) maximum temperature STC.

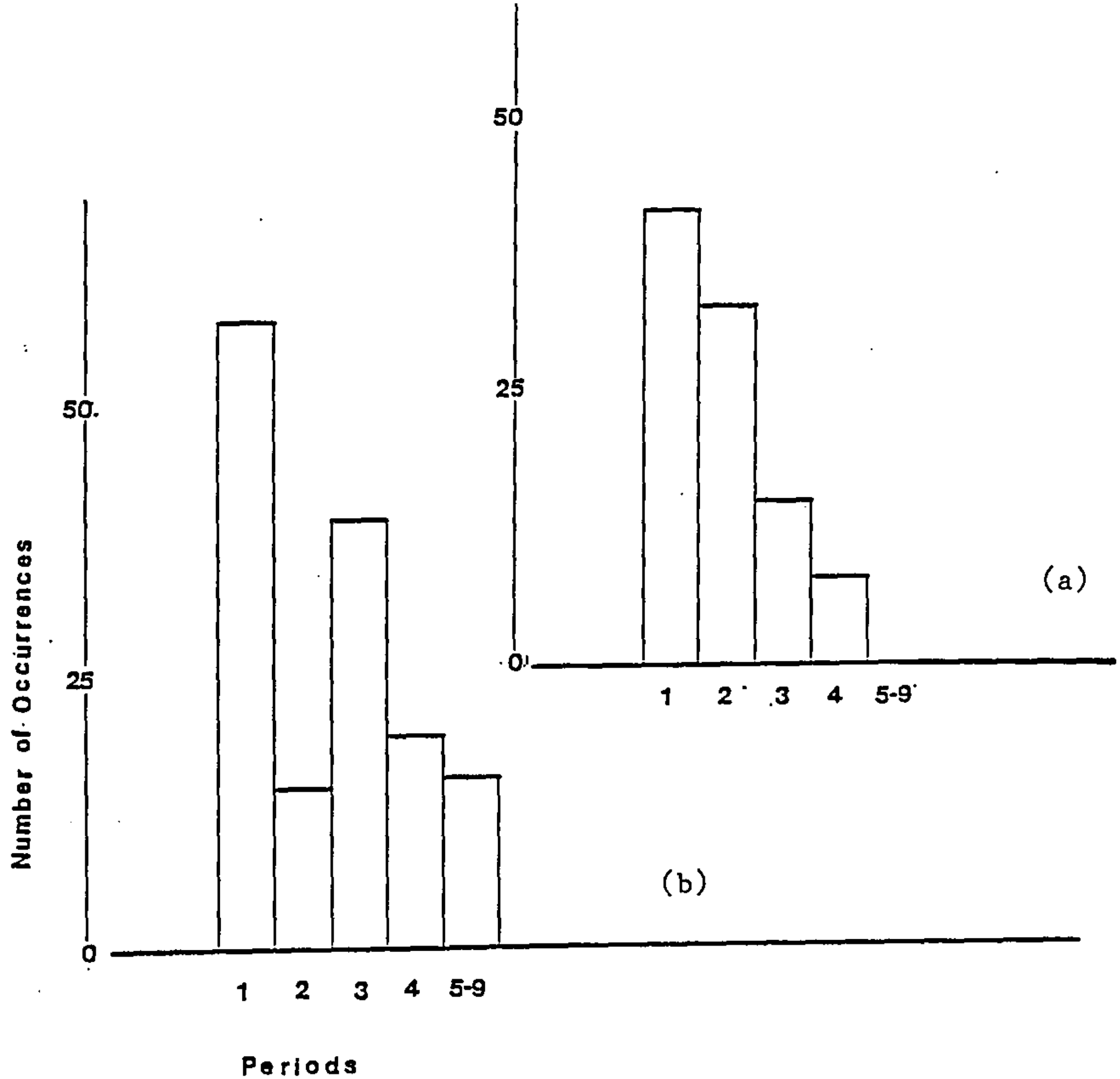



Fig. 6. Cool season time periods 1980-1985 (a)minimum temperature STC, (b) maximum temperature STC.

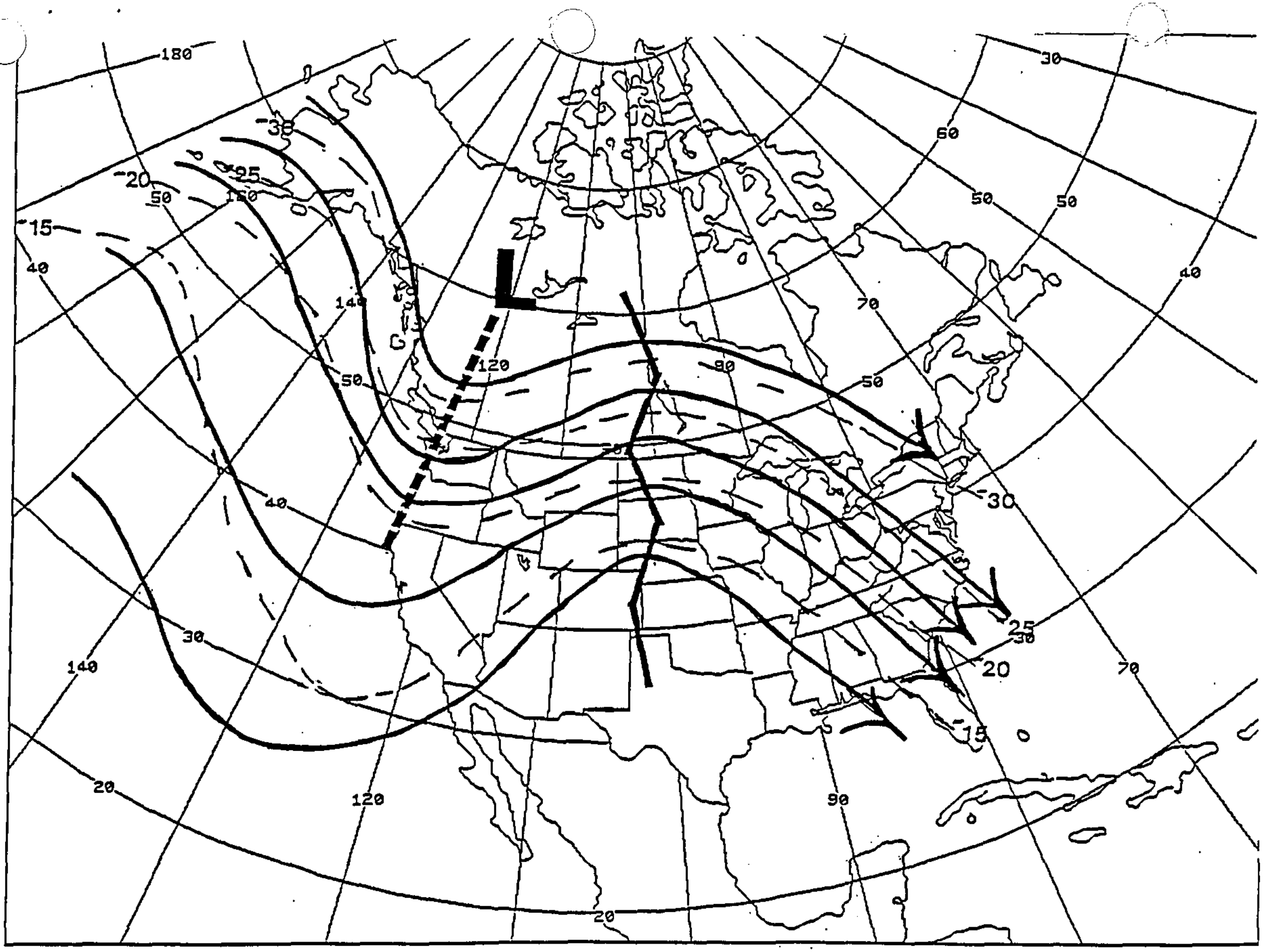



Fig. 7. Composite 500 mb map for the warm season STC occurrences.

Northwest trough and associated cold front bring colder temperatures to Wyoming. The 500 mb temperatures with this warm season trough are between -20 to -30°C.

B. Cool Season

Most of the cool season STC occurrences are in December and January when Wyoming is influenced by strong zonal flow and migratory surface fronts. Fundamentally, the 500 mb pattern for cool season events is comprised of rapidly progressing northwesterly or westerly short wave troughs embedded in the flow.

Figure 8a exhibits the 500 mb northwest flow type which is most common with cool season STC's. It consists of a weak upper level ridge over Wyoming and a strong and fast moving short wave trough over the Pacific Northwest. This northwest pattern has an associated surface cold front, which quickly crosses through Wyoming with cold temperatures building in behind the front.

The second most common cool season pattern at 500 mb is a strong short wave trough off the California coast (Fig. 8b). This westerly trough also has an associated surface cold front which moves with it across Wyoming. These cool season troughs have 500 mb temperatures between -25 to less than -35°C.

5. Conclusions

Major conclusions are:

A. For the years examined, the monthly mean maximum and minimum temperatures were within two standard deviations from the 30-year mean. Therefore, the temperatures can be regarded as normal. It was found that temperatures at Cheyenne and Rock Springs had little temporal variability for the warm season. Sheridan exhibited marked variability for the cool season.

B. A weak spatial effect on STC events was detected during the warm season. Spatial separation had a greater effect on STC for the cool season, particularly, the minimum STC events.

C. During the warm season, the highest incidence of STC events occurs in April and September. The average monthly number of STC days during the warm season for maximum temperatures ranged from five days in July to ten days in April and September. The average monthly number of STC days for minimum temperatures ranged from three days in July to seven days in April and September.

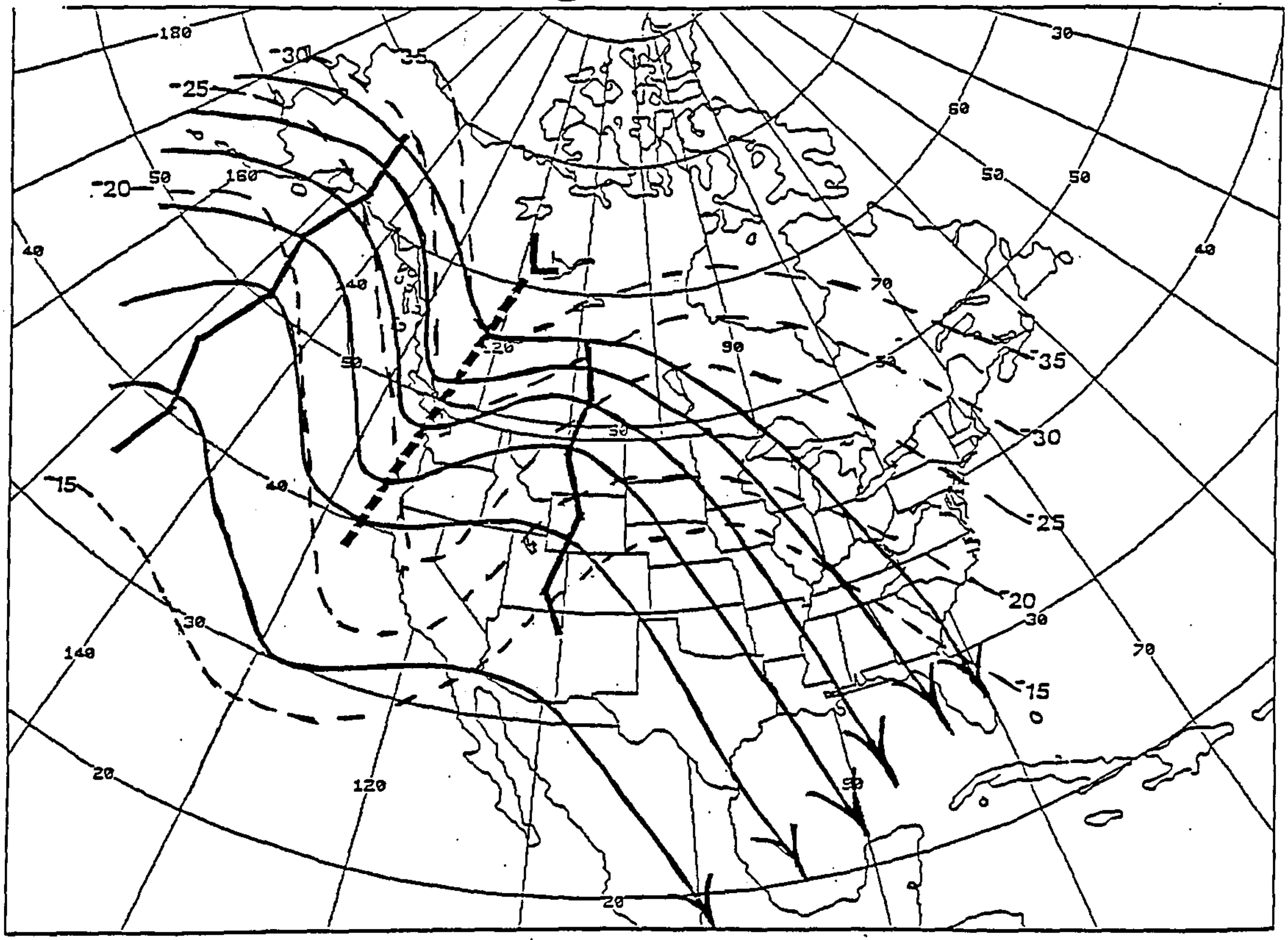



Fig. 8a. Composite 500 map for the northwest flow type for the cool season STC occurrences.

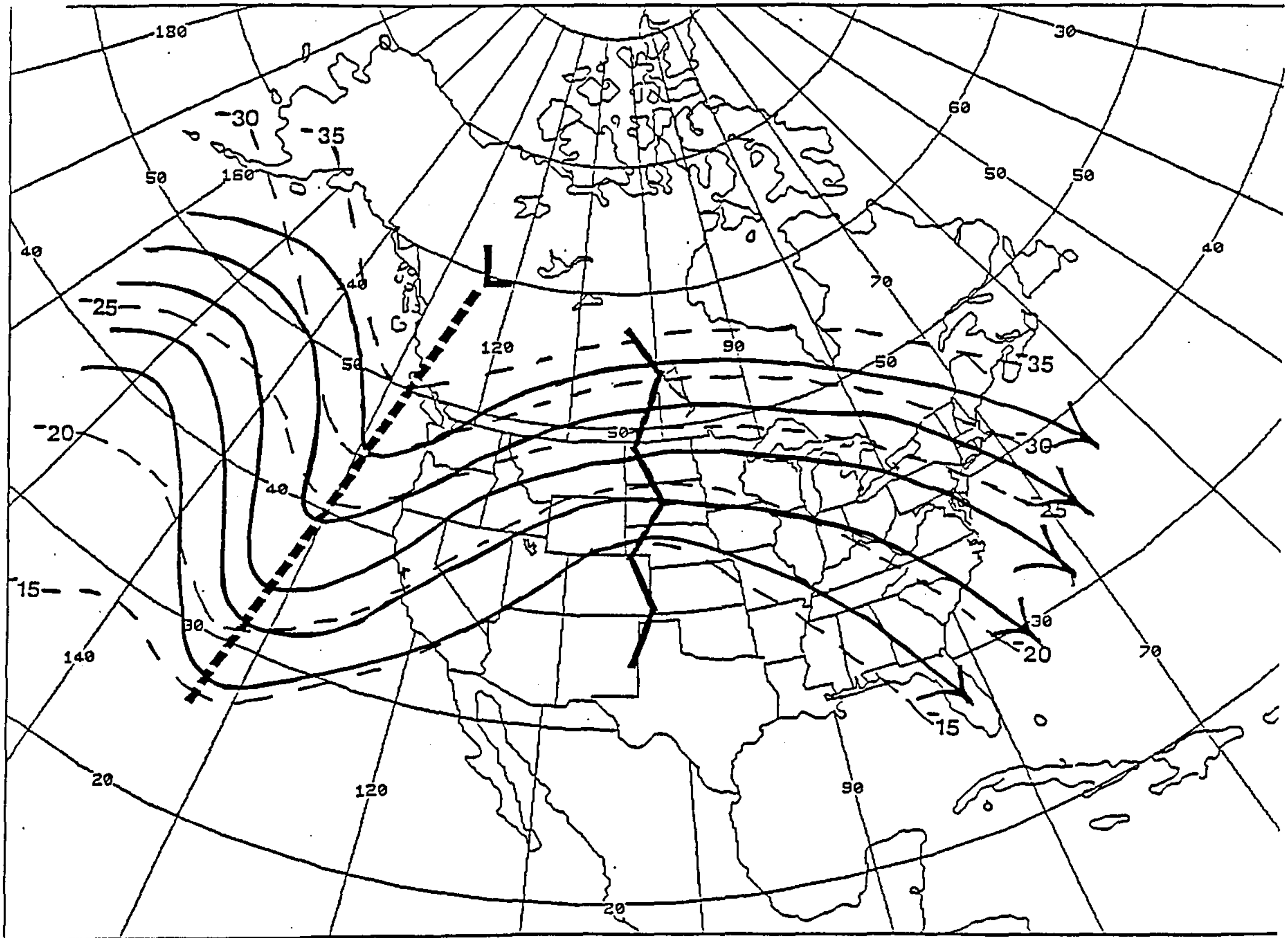



Fig. 8b. Composite 500 mb map for the west flow type for the cool season STC occurrences.

D. The cool season showed the highest occurrence of STC events during December and January. The average monthly number of STC days during the cool season for maximum temperatures ranged from seven days in February, March, and November to nine days in December and January. The average monthly number of STC days for the minimum temperatures ranged from five days in March to 11 days in December.

E. During the warm season STC's typically occurred on two consecutive days. In contrast, the cool season showed single day STC occurrences.

F. A subjective composite 500 mb pattern was derived for the two-day length of STC events of the warm seasons. It consists of an upper level ridge east of Wyoming, with a fairly strong short wave trough (and associated surface front) over the Pacific Northwest.

G. The subjective composite 500 mb patterns for the one-day length STC events for the cool seasons were broken down into two short wave troughs. These troughs consisted of either a northwesterly or a westerly type.

## 6. Acknowledgements

I wish to thank Jack Daseler and Mike Weiland for the time and effort they spent helping me to edit this paper. Thanks are also due to William T. Parker and Kenneth R. Rizzo for their useful and constructive comments.

## 7. References

Griffiths, F., 1976: North America. World Survey of Climatology. Elsevier Scientific Publishing Company, Amsterdam, 24, 37.

Martner, B.E., 1986: Wyoming Climate Atlas. Univ. of Nebraska Press, Lincoln, 20-24.

National Weather Service, 1980-1985: Daily weather maps. NOAA, NWS, National Meteorological Center, Silver Spring, MD.

Pieke, R.A. and N. Waage, 1987: Note on a definition of normal weather. Nat. Wea. Dig., 12, 20-22.

Tout, D. G., 1987: The variability of air frost in Great Britain. Weather, 42, 268-273.

CENTRAL REGION APPLIED RESEARCH PAPER 99-5

# A QUICK LOOK AT TERMINAL FORECASTS FOR CASPER AND CHEYENNE, WYOMING: ARE THEY TOO PESSIMISTIC?

James P. Kramper and Michael S. Weiland
National Weather Service Forecast Office
Cheyenne, Wyoming

## 1. Introduction

Weather forecasting to support aviation is a very important and challenging part of the National Weather Service mission. Terminal forecasts are used in planning and executing thousands of flights daily. Of utmost concern is safety. But, also, a growing concern involves the economic impact terminal forecasts have on the aviation system.

Covey (1987) noted a United Airlines study which estimated it costs $3,000 to $6,000 a day to carry extra fuel when clouds and/or visibilities below critical thresholds were forecast at a major terminal. This was regardless of whether or not the forecast conditions actually occurred. The same study estimated the total cost to airlines was over $16 million per year in the United States, due to forecast of adverse conditions which did not occur.

The purpose of this study was to determine if the terminal forecasts for Casper (CPR) and Cheyenne (CYS), Wyoming, were overforecasting adverse conditions, and if they were, at what frequency.

## 2. Procedure

The majority of air traffic at both CPR and CYS are visual flight rule (VFR) flights. So, for this study, "adverse conditions" were considered to be weather at or below marginal VFR (ceilings three thousand feet or lower and/or visibilities six miles or less). The period examined was November 1987 to March 1988. These months were chosen because they are the months when conditions below VFR are most likely to occur.

Each terminal forecast was examined and placed in one of four categories. These categories included:

1. VFR forecast and observed (VFR verified),
2. VFR forecast and MVFR or less observed (VFR miss),
3. MVFR or less forecast and observed (MVFR verified), and
4. MVFR or less forecast and VFR observed (MVFR miss).

A terminal forecast was considered a MVFR forecast even if the MVFR criteria was only mentioned as the result of using the OCNL, CHC or SLGT CHC categories. This procedure was followed since pilots must always file flight plans and carry fuel to cover the worst possible conditions, no matter what the chance of the conditions occurring.

A terminal was considered to "verify" if the forecast conditions occurred during the valid period of the terminal, regardless of timing or probability. Similarly, a terminal was considered a "miss" if actual conditions differed categorically from the forecast throughout the valid time. The outlook period of the terminal forecast was not considered.

## 3. Results

Tables 1 and 2 show the results of the study broken down by month and Table 3 gives the totals for all months examined. The results were very consistent.

The worst months, percentage wise, for MVFR "miss" forecasts at CYS were December with 36 percent and January with 18 percent. In CPR, most of this type of miss occurred in January with 27 percent and November with 25 percent. The totals show that CYS was overforecast (MVFR misses) on 29 occasions, or 17 percent of the time. CPR was overforecast on 27 occasions, or 16 percent of the time.

In the VFR "miss" forecast group, the worst months for CYS were March with 45 percent and January with 23 percent. For CPR, the results were very close with January having missed 24 percent and March 23 percent. While the number of forecasts differ, the results for this group of VFR forecasts came out with the same percentages. CYS was underforecast 49 times, or 17 percent. CPR had 46 VFR misses, or 16 percent.

Considering the terminal forecast for CYS and CPR, it does not seem that overforecasting is a serious problem concerning the terminal forecasts for CYS and CPR. In CYS, MVFR conditions did not verify only 17 percent of the time. For CPR the percentage was 16 percent.

While these may be acceptable numbers, they probably could have been lower. Quite a few of the MVFR misses were due to marginal conditions that were introduced in the terminal forecast as a "slight chance" condition. It is suspected that forecasters often try to cover any and all possibilities. Unfortunately, this can produce a terminal forecast which is not of much use to the user. As a general rule, terminal forecasts should have a MINIMUM of variability terms.

Tables 1 and 2 also seem to show a pattern for both CYS and CPR throughout the winter months. During the 1987-1988 season, the forecasters seemed to overforecast marginal conditions early in the season, as can be seen by the relatively high number of MVFR misses in November and December.

The opposite was true of the late winter months, especially March. At this time, the forecasters were often too optimistic, forecasting VFR weather when marginal conditions would have verified.

TABLE 1
CHEYENNE

| | FORECAST VFR | ACTUAL WEATHER | | FORECAST MVFR | ACTUAL WEATHER | |
|---|---|---|---|---|---|---|
| | | VFR % | MVFR % | | MVFR % | VFR % |
| NOV | 56 | 56 (100) | 0 (0) | 34 | 29 (85) | 5 (15) |
| DEC | 54 | 51 (94) | 3 (6) | 39 | 25 (64) | 14 (36) |
| JAN | 64 | 49 (77) | 15 (23) | 29 | 25 (82) | 4 (18) |
| FEB | 53 | 47 (89) | 6 (11) | 34 | 29 (85) | 5 (15) |
| MAR | 55 | 30 (55) | 5 (45) | 38 | 37 (97) | 1 (3) |

TABLE 2
CASPER

| | FORECAST VFR | ACTUAL WEATHER | | FORECAST MVFR | ACTUAL WEATHER | |
|---|---|---|---|---|---|---|
| | | VFR % | MVFR % | | MVFR % | VFR % |
| NOV | 62 | 56 (90) | 6 (10) | 17 | 12 (71) | 5 (29) |
| DEC | 61 | 55 (90) | 6 (10) | 28 | 21 (75) | 7 (25) |
| JAN | 62 | 47 (76) | 15 (24) | 33 | 24 (73) | 9 (27) |
| FEB | 54 | 47 (87) | 7 (13) | 33 | 27 (82) | 6 (18) |
| MAR | 52 | 40 (77) | 12 (23) | 41 | 38 (93) | 3 (7) |

TABLE 3
TOTAL FORECASTS

| CHEYENNE | | | CASPER | | |
|---|---|---|---|---|---|
| VFR FORECASTS | | | | | |
| TOTAL | HITS | MISSES | TOTAL | HITS | MISSES |
| 282 | 233 (83%) | 49 (17%) | 291 | 245 (84%) | 46 (16%) |
| MVFR FORECASTS | | | | | |
| TOTAL | HITS | MISSES | TOTAL | HITS | MISSES |
| 174 | 145 (83%) | 29 (17%) | 167 | 140 (84%) | 27 (16%) |

## 4. Conclusion

Over or underforecasting MVFR or less conditions can pose serious safety and economic problems for commercial and general aviation. Terminal forecasts, in general, as shown by looking at CPR and CYS, probably have too many possibilities in the forecast. It is always best to use as few of the categories outside of the prevailing category as possible. This statement has been corroborated through discussions with both commercial and general aviation pilots. The results of this paper suggest that the best service to aviation interests results from better resolution in the forecast and not just generalized terminology which attempts to avoid the issuance of amendments.

## 5. References

Covey, D. L., 1987: Introduction To Aviation Terminal Forecasting. NWSTC Forecaster Development Module MMFDC250. Available from NWS Training Center, Kansas City, MO.

Jackson, R., 1984: Terminal Forecast Pitfalls. Western Region Technical Attachment No. 84-07. Available from NWS Western Region, Scientific Services Division, Salt Lake City, UT.

CRH SSD
CRARP 99-6

# CENTRAL REGION APPLIED RESEARCH PAPER 99-6

# TERRAIN ENHANCED SNOWFALL ON THE SHORES OF WESTERN LAKE SUPERIOR - A CASE STUDY - DECEMBER 13TH AND 14TH, 1988

Byron A. Paulson
National Weather Service Forecast Office
Minneapolis, Minnesota

Carol L. Christenson
National Weather Service Office
Duluth, Minnesota

## 1. Introduction

Even in the relative flatlands of Minnesota, terrain can play a significant role in the enhancement of snowfall. Also, in borderline cases, there is enough elevation change in parts of Minnesota to make the difference between the occurrence of a rain/slush and a snow event. This was documented in a southern Minnesota case study by Paulson (Central Region Technical Attachment 84-23). This study will take a look at terrain enhancement in northeast Minnesota and northwest Wisconsin, near the shore of Lake Superior, where the most dramatic elevation changes in these states occur.

On December 13th and 14th, 1988 a swath of snow swept across northern Minnesota, through the Duluth area, and into northwest Wisconsin. A plot of snowfall reports (Fig. 1) delineated an area of increased snowfall on the rapidly rising terrain in the vicinity of Lake Superior.

This storm was a very interesting one in itself as it generated more snow than is typically associated with storms that sweep southeast out of the western Canadian provinces. It deposited a swath of six inch snow totals in a band 30 to 40 miles wide stretching from near the Grand Forks area of North Dakota through the Duluth area and into northern Wisconsin. Snow totals ballooned into ten inch range in the high terrain in the Duluth vicinity and into northwest Wisconsin.

## 2. Geography Considerations

The Duluth area, which is located at the extreme western head of Lake Superior, is certainly not the ideal location to conduct a terrain or lake snow study since there is a relatively narrow window which furnishes a trajectory off the lake. However, the metro area does afford a relatively abundant source of reports. Data become a scarce commodity in areas farther east along the south shore of the lake where terrain or lake enhanced snows are more common.

Terrain rises abruptly, by Minnesota standards, along the shores of Lake Superior (Fig. 2). The highest terrain in the state is found within about 20 miles of the lake shore. Hills in Duluth rise to a height of about 1400 feet above mean sea level within a few miles of the lake (elevation about 600 feet msl). Across the St Louis Bay, in extreme northwest Wisconsin, the slope is less abrupt with the steep terrain rises lying back about ten miles from the lake. Farther east into northwest Wisconsin, elevation rises again become more abrupt with the steepest slopes once again concentrated closer to the lake shore.

## 3. Synoptic Situation

The 1200 UTC Tuesday, December 13th RGL initialized analysis showed a potent vorticity maximum near Calgary, Alberta with an accompanying surface low of 992 mb also in the vicinity of Calgary (Fig. 3). This storm exhibited the very rapid southeast movement characteristic of northwest flow storms. The surface low surged southeastward at over 40 knots reaching the Bismarck, North Dakota area by 0000 UTC Wednesday and central Wisconsin by 1200 UTC Wednesday. Precipitable water values were not exceptionally high - generally in the .30 to .45 inch range.

Excellent PIVA generated by a strong vorticity maximum running along a tightly packed thickness field (Fig. 4) spread snow east well ahead of the surface low and contributed to high snowfall amounts. A slight difluence in the thickness field across northern Minnesota was another positive factor favoring the generation of significant snow. The main snow band was about one degree to the left of the path of the vorticity max in line with studies done by Younkin (1968).

It is worthwhile to note that the RGL handled the positioning of major forecast features quite well. As far back as the 36 hour forecast package from 0000 UTC December 13th the RGL consistently indicated the Alberta vorticity maximum would be in north central Wisconsin by 1200 UTC the 14th. The position of the surface low at 1200 UTC Wednesday was within 60 miles of the 36 hour RGL forecast with each succeeding forecast position and strength showing an improvement.

Less success was exhibited by the MOS precipitation guidance. It gave little indication that this storm would be a heavy snow event. The 1200 UTC December 13th MOS guidance forecast a 60 percent probability of measurable precipitation for Duluth for the coming night. However, the POSA conditional probability gave only a 15 percent chance of two inches or more of snow and only a two percent chance of four or more inches.

## 4. The Local Situation

It can be difficult to separate enhancement due to terrain from that due to the simple contribution of additional moisture into the air mass from a trajectory over the open waters of the Great Lakes. However, we can immediately eliminate this case as a true lake snow event in the classical

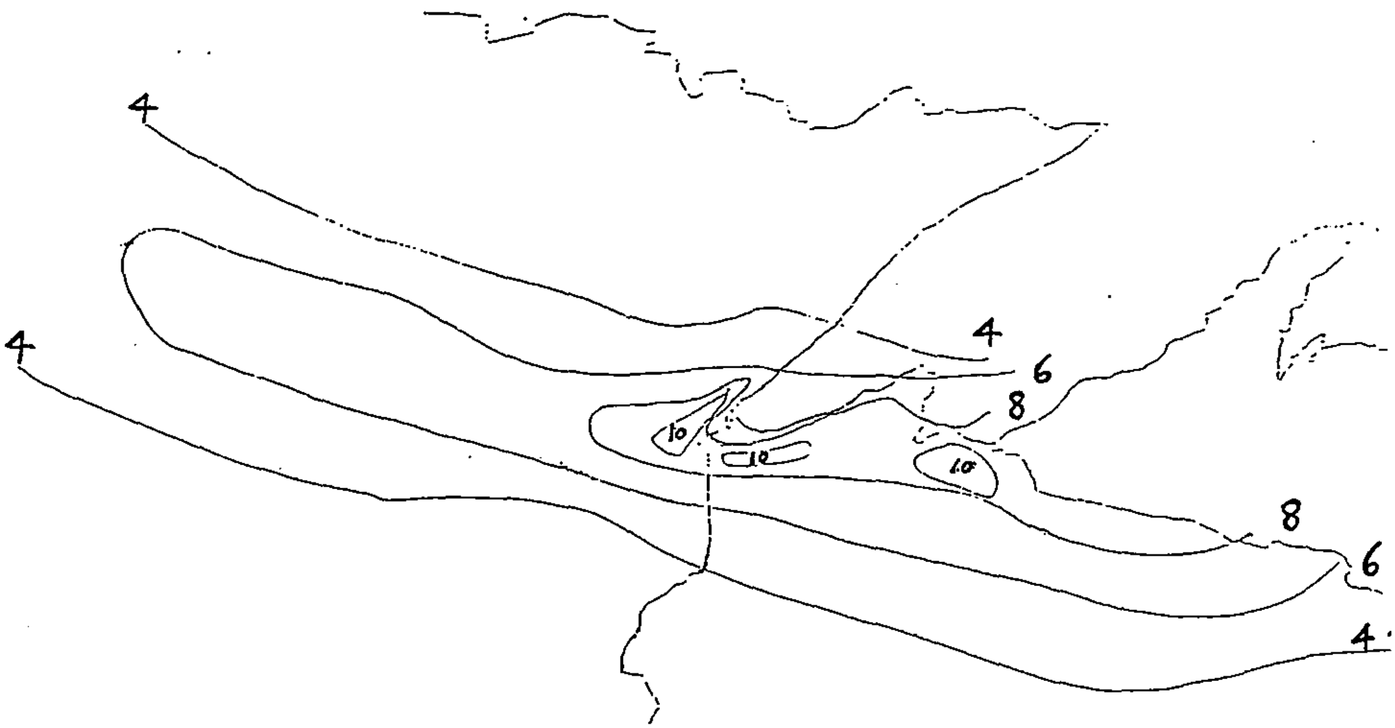



FIG 1. Snowfall totals December 13 and 14, 1988. Analysis of nearly 100 reports of data including NWS Cooperative reports and Minnesota Snowfall Network reports.

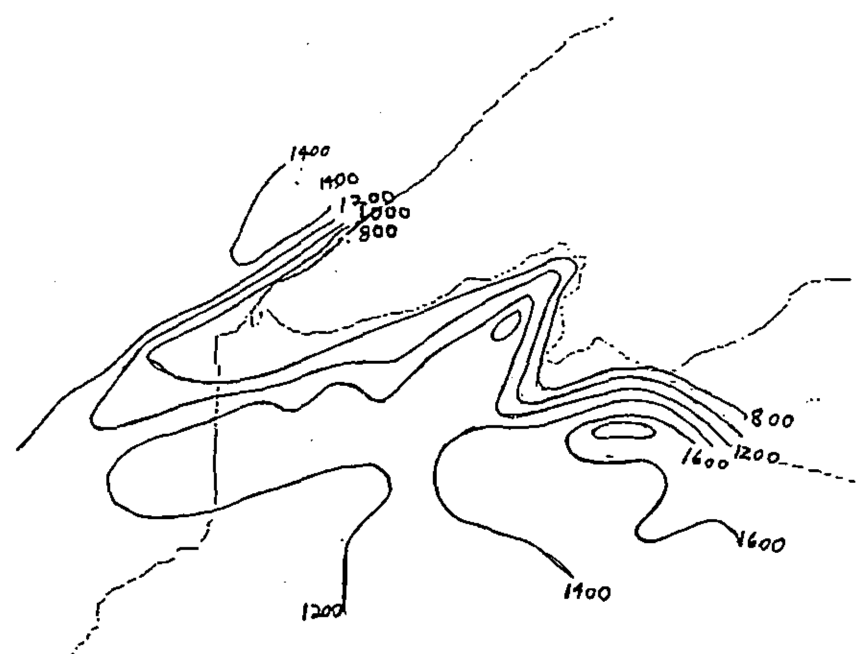



FIG 2. Topographic analysis at 200 foot intervals across snowfall area.

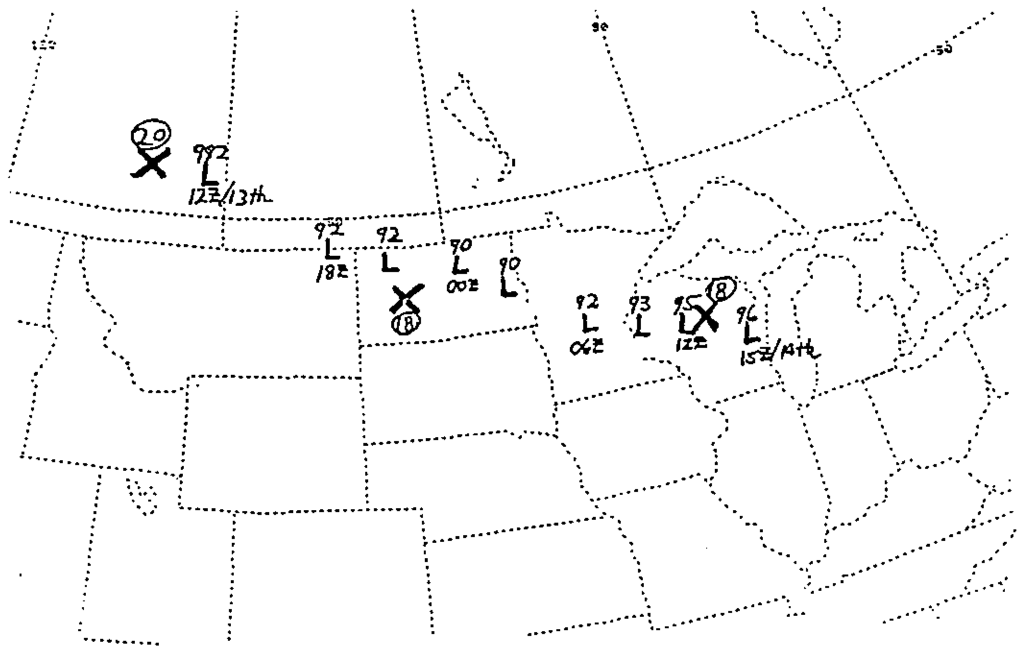


Fig. 3. Surface low position (L) and central pressures at 3 hourly intervals from 1200 UTC December 13th to 1500 UTC December 14th. Also, 500 mb RGL initialized vorticity maxima positions (X) and strengths at 1200 UTC December 13th, 0000 UTC December 14th, and 1200 UTC December 14th.

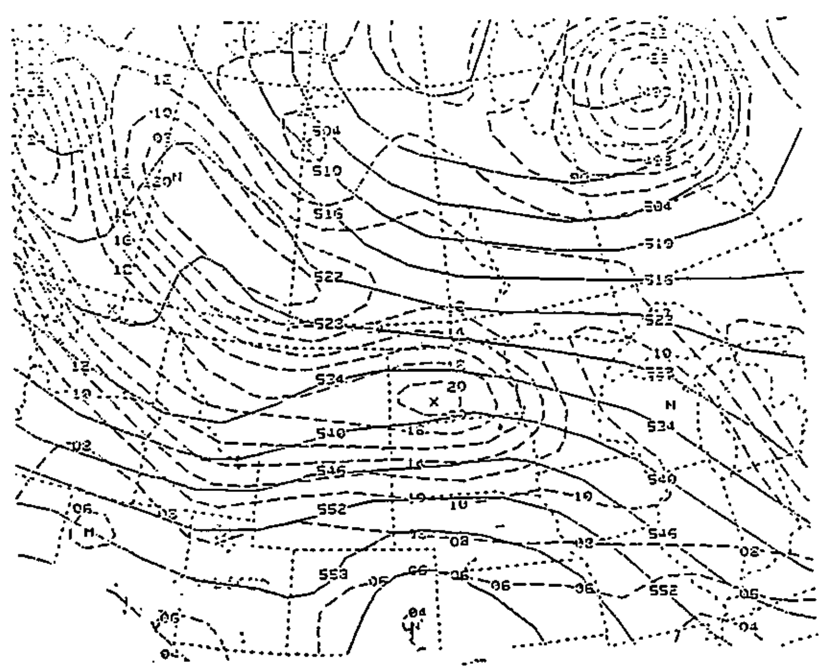


Fig. 4 0000 UTC December 14th RGL initialized analysis of 1000 to 500 mb thickness (solid) and 500 mb vorticity (dashed).

sense of the definition. Since the heavy snows in this case occurred ahead of and in the vicinity of the surface low, they were not associated with strong cold advection in the wake of the low where convective lake effect snow squalls develop in an environment of strong low level instability.

This still leaves us with the question of which factor did dominate, terrain effects or additional available lake moisture. In this case it is likely that the dominant contribution was from the additional lift over the terrain. Snowfall amounts at reporting stations near lake level were, in general, significantly less than those reported by nearby stations at higher elevations. Along the south shore of Lake Superior, in northwest Wisconsin, snowfall amounts at stations within 200 feet of lake elevation ranged from five to seven inches. These amounts were in the general range of the snowfall across northern Minnesota. As steeper terrain and higher elevations were encountered snowfall amounts increased into the eight to ten inch range. In extreme northwest Wisconsin, at the City of Superior, a six inch snowfall was reported. About ten miles south of Superior, in the Pattison Park area, northeast winds pushed air up the rising terrain and snowfall accumulations into the ten to 12 inch range were observed.

In the Duluth area terrain enhancement was very evident. In Downtown Duluth, at elevations within a couple hundred feet of the Lake, snowfalls were typically in the six to eight inch range. Amounts increased at the summit of the hills and about 20 miles inland to the ten inch range with a few reports near 12 inches (Fig. 5).

Wind directions at the Duluth WSO during the time of heaviest snowfall (0500 UTC to around 1030 UTC December 14th) were from 040 to 080 degrees with speeds in the six to ten knot range. The Coast Guard Station on the lake front reported winds of 11 to 14 knots from the northeast. Sangster wind speeds and directions during the snow episode are shown on Fig. 6. Geostrophic wind directions were off the lake during the period of heaviest snowfall. Frictional effects turned the winds to a more northeastern direction and decreased their speed. This provided good upglide over the terrain south of the WSO where some of the heaviest snows occurred. Mass convergence from frictional effects also helped to result in relatively strong upward vertical velocities. Assume a wind off the lake with a 15 knot component normal to the terrain. Then $V \cdot \tan \theta$ (where $\theta$ is the slope of the terrain) yields a vertical velocity of almost 40 cm/sec (about 40 microbars/sec). Remember that a synoptic scale 700 mb vertical velocity of 3 cm/sec is approaching the strong range. Terrain induced vertical velocities into the Duluth vicinity thus were about an order of magnitude larger than the synoptic scale lift.

It should also be noted that the 1200 UTC December 13th MOS indicated winds would be from a direction of 350 to 020 during the period that heavy snow occurred at Duluth. Observed winds at the Duluth WSO were 40 to 60 degrees more easterly than MOS forecast. If winds had actually blown as forecast by MOS, downslope winds would have occurred across the Duluth metro

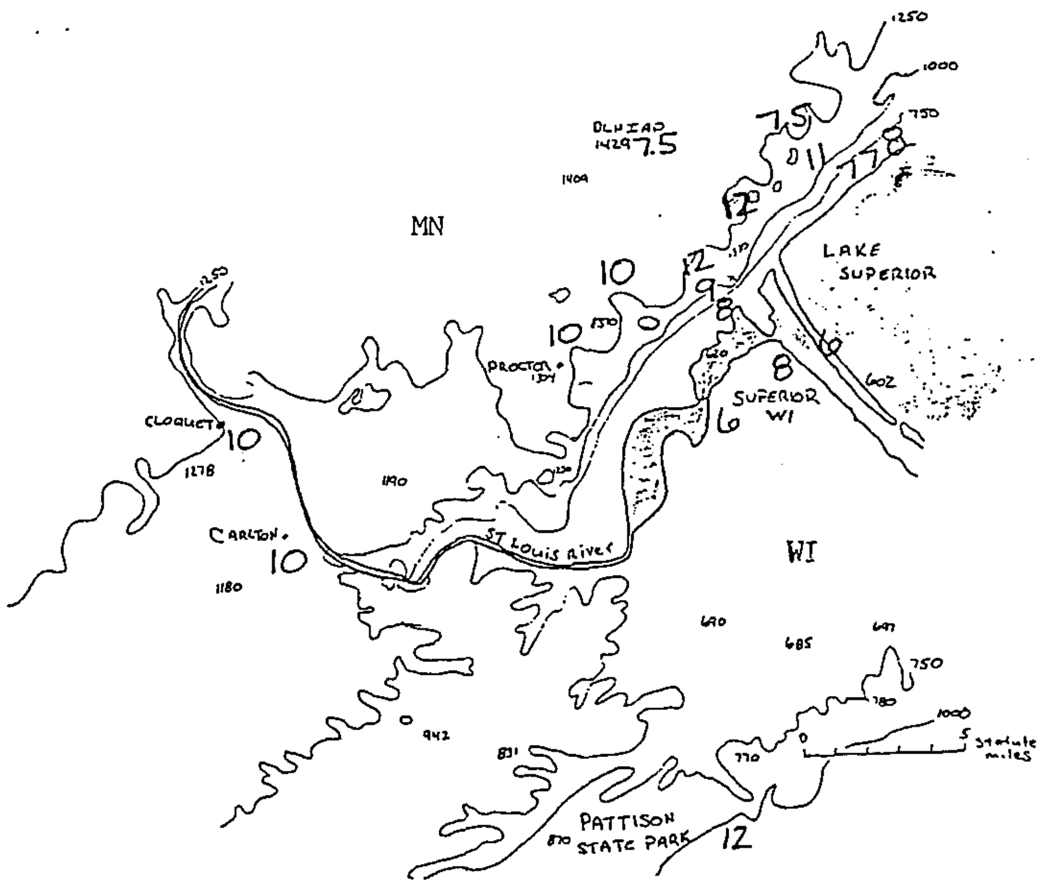



FIG. 5 250 foot interval topographic map of Duluth-Superior vicinity. Snowfall totals are indicated by bold numbers.

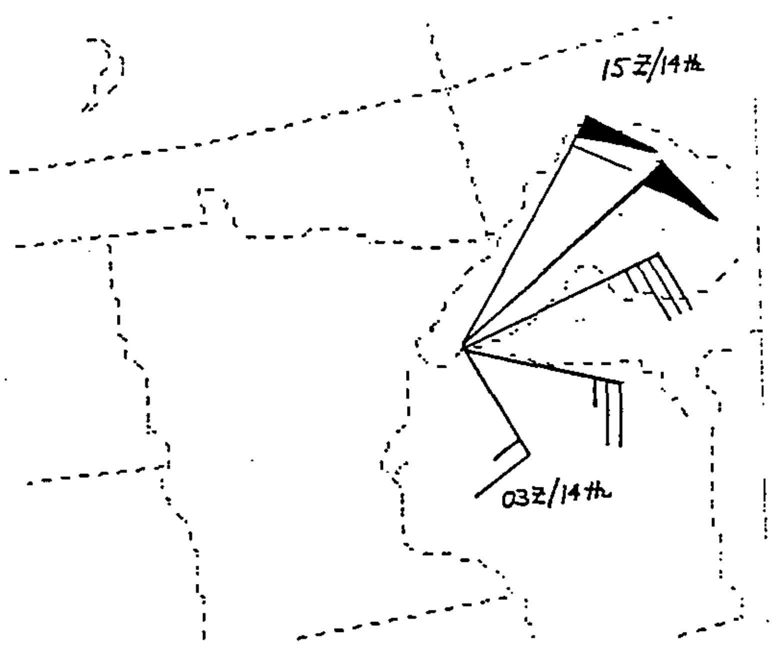



Fig. 6 Sangster winds at three hourly intervals encompassing the snowfall event.

area and lesser snow amounts undoubtedly would have occurred. Terrain enhanced snows would then have been confined farther east along the south shore of Lake Superior.

## 5. Conclusions

Even in Minnesota it is wise to consider the potential of topography when forecasting snowfall. In this case snowfall amounts were increased by 30 to 40 percent primarily from topographic forcing. Application of one's knowledge of local terrain influences on weather can pay big dividends. Relatively minor variations in wind direction at a station such as Duluth can make a significant difference in snowfall.

## 6. Reference

Paulson, B. A., 1984: The Effect of Topography on Snowfall in Southern Minnesota, A Case Study. Central Region Technical Attachment 84-23, available from NWS Central Region, Scientific Services Division, Kansas City, MO.

Younkin, R. J., 1968: Circulation Pattern Associated with Heavy Snowfall over the Western United States. Mon. Wea. Rev., 96, 851-857.

# CENTRAL REGION APPLIED RESEARCH PAPER 99-7

# SOUTHERN LAKE MICHIGAN SEICHES ... SUMMER 1988

Jane A. Hollingsworth
National Weather Service Forecast Office
Chicago, Illinois

## 1. Introduction

Nearly 35 years ago, on June 6, 1954, a 10 foot wave rose suddenly from a placid Lake Michigan, sweeping eight fishermen off of a breakwater at the entrance to Montrose Harbor to their deaths. The "killer wave" had actually bounced off of the east shore of Lake Michigan back to the Chicago lake front. The phenomena is known as a "seiche," pronounced "saysh." A seiche is defined as "a continuation of a water-level disturbance after the external forces causing the disturbance have ceased to act."

On the Great Lakes, especially lower Lake Michigan, significant seiches are caused by fast moving lines of thunderstorms, or squall lines. The strong downdraft winds and pressure jump created by the line form a long shallow wave which causes a surge of water on the east shore of the Lake, at about the same time as the thunderstorms pass there. This wave is then reflected back to the west shore, and the resulting water level fluctuation at that point is termed a seiche (Fig. 1).

This scenario was explained by Hughes (1970) using an excellent analogy. If you were to dunk a doughnut into a cup of coffee, the level of the coffee would rise around the doughnut. When the doughnut was removed, the coffee would slosh back and forth in the cup for a time before coming to rest. The dunking of the doughnut is analogous to the pressure exerted on the water surface by the squall line; the sloshing of the coffee back and forth similar to the water fluctuations observed during a seiche.

The initial wave created by a squall line is very long, maybe up to 20 miles, but only a few inches high in the deep water. The deeper the water, the faster the wave moves. The wave in Lake Michigan, because of its' depth, could move at 60 to 120 mph.

The speed of the thunderstorms is the key factor, because a significant seiche won't occur unless the squall line moves at the same speed as the water wave. The critical direction and speed of movement for a seiche-producing squall line is from the northwest (about 340 degrees) at around 55 knots. The actual build-up of height of this "small" wave occurs when the wave moves into shallow depths. Friction slows the forward edge while the

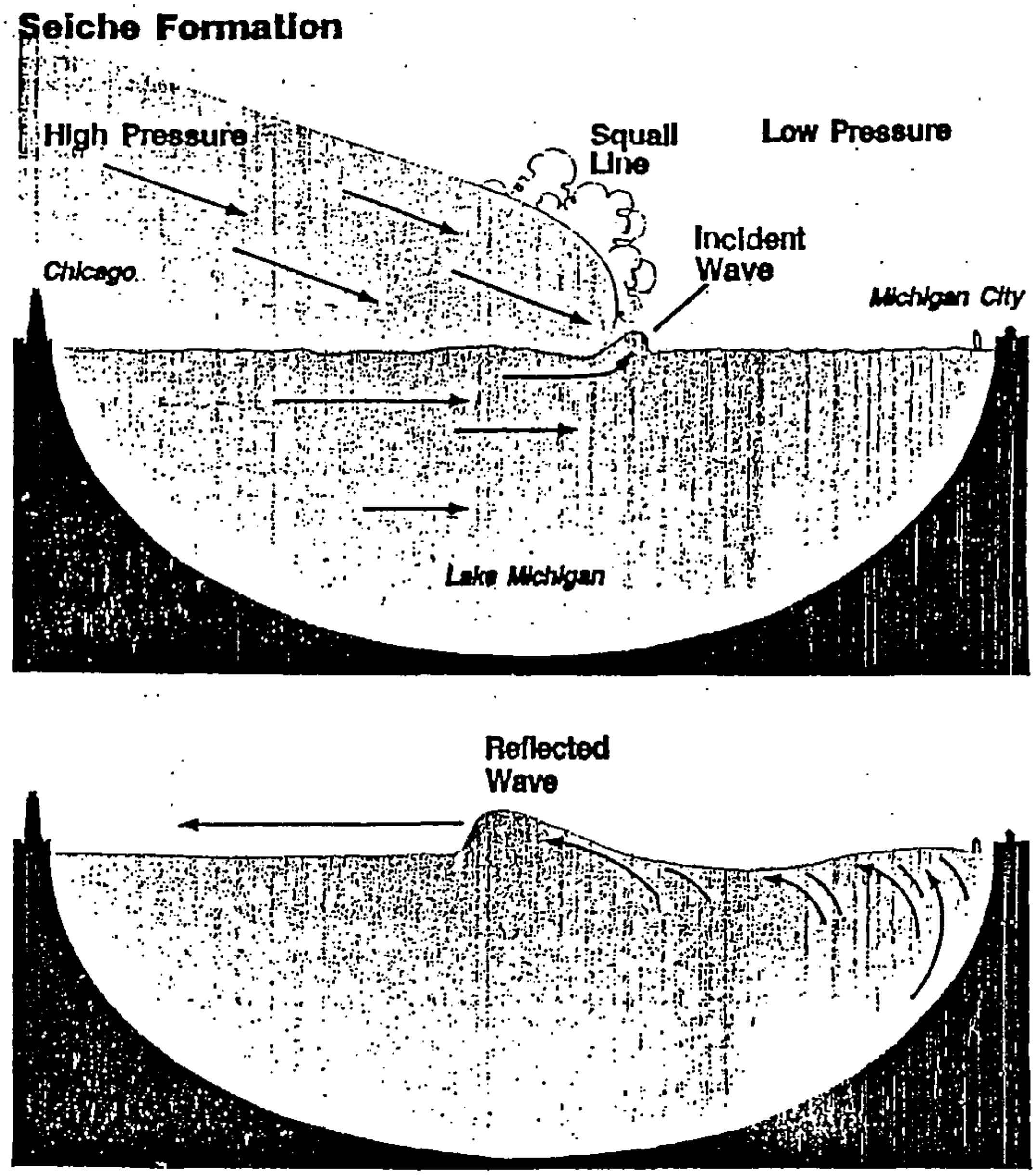



Fig. 1

After a storm line has shoveled water across the lake basin, forming an incident wave, it sloshes back to the other shore in a reflected wave. The seiche that killed eight people in Chicago in 1954 was a reflected wave.

Seiches occur in enclosed bays or basins like the lower end of Lake Michigan when a storm with a pressure gradient moves across at high speeds, pushing water ahead of it.

Reprinted from Chicago Tribune Magazine; Aug. 18, 1985, pp. 54-61, from "The Big Wave" by W. Gordon back edge continues at a rapid rate, causing a piling up of the water. Once the squall line passes the city of Chicago, it generally takes about 1 1/2 to 2 1/2 hours before the returning seiche hits the Chicago area lake shore. The seiche has two parts.

First, there is a rise of water at the lake shore. The rise can be gradual and rather undramatic, or it can be sudden and powerful, as in the 1954 case. With this first stage, the risk is to persons out on long piers that may not have time to reach shore, or perhaps to children playing in the previously shallow and calm water.

Second, there is the withdrawal of the water, which is sometimes more spectacular than the rise. Risks at this point are to boats, generally 200 to 400 yards from shore, where the fluctuations can be disastrous. Vessels have been known to hit the bottom of their respective harbors as the water level drops. Docked boats can also be affected as the water level changes and stretches lines beyond their limits, actually tearing the lines or damaging vessels.

The maximum rise of water is usually about four feet on the east shore of Lake Michigan, and up to eight feet or more on the west shore. Several lesser surges will occur at about 30 minute intervals after the initial peak surge. This sloshing of the water back and forth in the Lake basin could continue for up to 24 hours (Fig. 2).

Since squall lines do not frequent the Great Lakes region anyway, a line of thunderstorms moving at "optimum" speed for a major seiche is somewhat of a rare event. In fact, there have only been five major seiches on the Chicago lake front in the past 35 years. They occurred on June 24 and July 6, 1954; August 3, 1960; June 7, 1980; and June 12, 1983. Water level changes were generally in the three to six foot range, except for the June, 1954 episode.

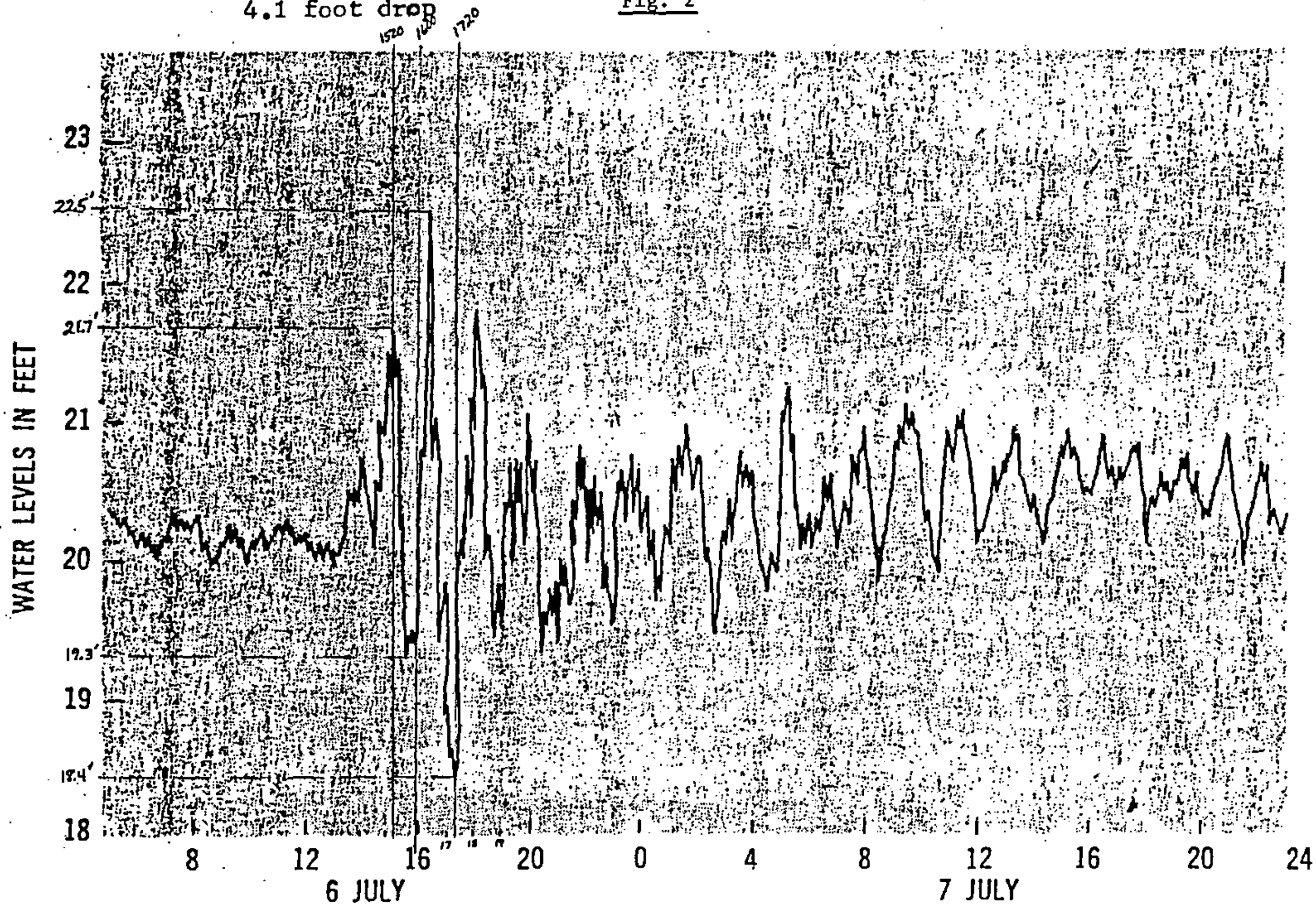
Compounding the problem of this "silent killer" is the time at which it strikes. The very nature of the seiche is such that it develops after an episode of stormy weather. However, in the wake of such a squall line, the weather is typically fair, with light winds. Lake enthusiasts have already ridden out the stormy weather and are ready to hit the water again as sunny skies and gentler winds prevail.

The forecasting problem regarding the seiche remains not so much in the timing of the event, but in the magnitude of the fluctuations. This could be due to the length of the squall line, which now can be determined from satellite and radar observations, but which is not, as yet, incorporated into the forecast scheme.

Other factors in determining the magnitude of a seiche involve the bathymetry of the lake basin and shape of the "reflecting" shore (in this case the east shore of Lake Michigan). These criteria seem to be "favorable" for seiches in the Chicago area.

*Note: 1520-1720
2.4 foot drop
3.2 foot rise
4.1 foot drop

Fig. 2




The 1954 seiche at Chicago, the first of these rare events to be forecast by the ESSA Weather Bureau. The magnitude is not as great as that close to shore, as the gage at the Wilson Ave. Crib is two miles offshore.

Reprinted from ESSA, "Seiche: the quiet killer", Oct. 1970, pp. 39, by L.A. Hughes

Fig. 2

## 2. Occurrences During the Summer of 1988

There were three noteworthy situations during the summer of 1988 in which seiches were reported along the Chicago lake shore. The occurrences were on June 22, July 15, and August 15. Water level drops associated with these situations were generally in the one to four foot range, so the seiches were relatively minor.

The first reported seiche in the Chicago area of the summer of 1988 occurred on June 22, and was reported around 1:45 p.m. CDT. It is not certain from the calls received at the Chicago NWS if this was the exact time of the level fluctuation.

Leonne Harbor (Fig. 3), on the far north side of the city, reported a one foot drop. Rainbow harbor, about 18 miles further south along the lake shore, had a 1 1/2 foot drop. South of there, at Calumet Harbor, the drop was three feet.

Satellite pictures from June 22 indicated an east-northeast to west-southwest line of thunderstorms extending from central Michigan across northwest Illinois into the southeast corner of Nebraska (Fig. 4). At 10:00 a.m. CDT, the strongest storms were across south central Lake Michigan to central Lake Huron. The line moved southeastward to the southern tip of Lake Michigan and northwest Indiana by 12:30 p.m. (Figs. 5 and 6), which was about 1 1/2 hours before the reported seiche at Chicago.

The Platzman (1965) technique was used to quantify amplitude of the seiche, using surface observations as well as radar and satellite information. The observations that were collected included those from Madison, Wisconsin; Milwaukee, Wisconsin; Rockford, Illinois; and Chicago, Illinois.

The average pressure jump at the above stations when the line of thunderstorms passed was .04 inches of mercury. The average speed and direction of the squall line was from 320 degrees at 20-25 knots. (Note that this is well below the critical speed of 50-60 knots.)

From this information, using Platzman's graph for Montrose Harbor (Fig. 7B), we get a factor of 3 to substitute into an operational prediction equation (Hughes, 1965) (Table 1). Hence,

$$7.5 \times .04 \times 3 = .9 \text{ feet}$$

Where 7.5 is an empirical factor derived to relate actual onshore surge heights to the computed offshore values of the Platzman graphs, and to incorporate wind stress effects, .04 is the pressure jump, and 3 is the number obtained from the Platzman graphs (Fig. 7) using thunderstorm direction and speed.

The direction of propagation and the relatively slow speed of the line could tend to favor a seiche greater magnitude toward the southern end of the basin, as noted by the three foot drop at Calumet. (At Gary, for

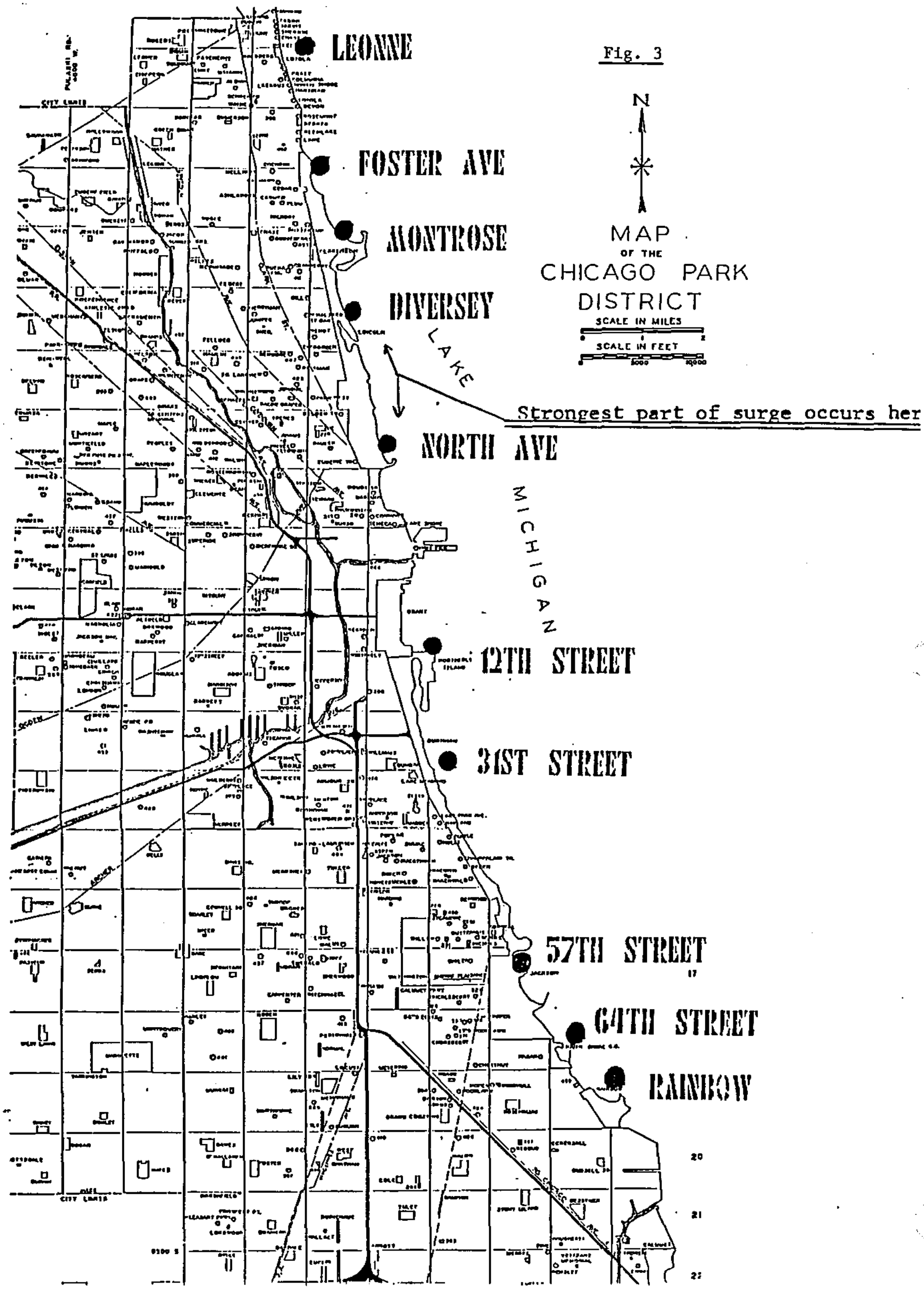


Fig. 3
N
MAP
OF THE
CHICAGO PARK
DISTRICT
SCALE IN MILES
SCALE IN FEET
LEONNE
FOSTER AVE
MONTROSE
DIVERSEY
LAKE
MICHIGAN
Strongest part of surge occurs her
NORTH AVE
12TH STREET
31ST STREET
57TH STREET
64TH STREET
RAINBOW

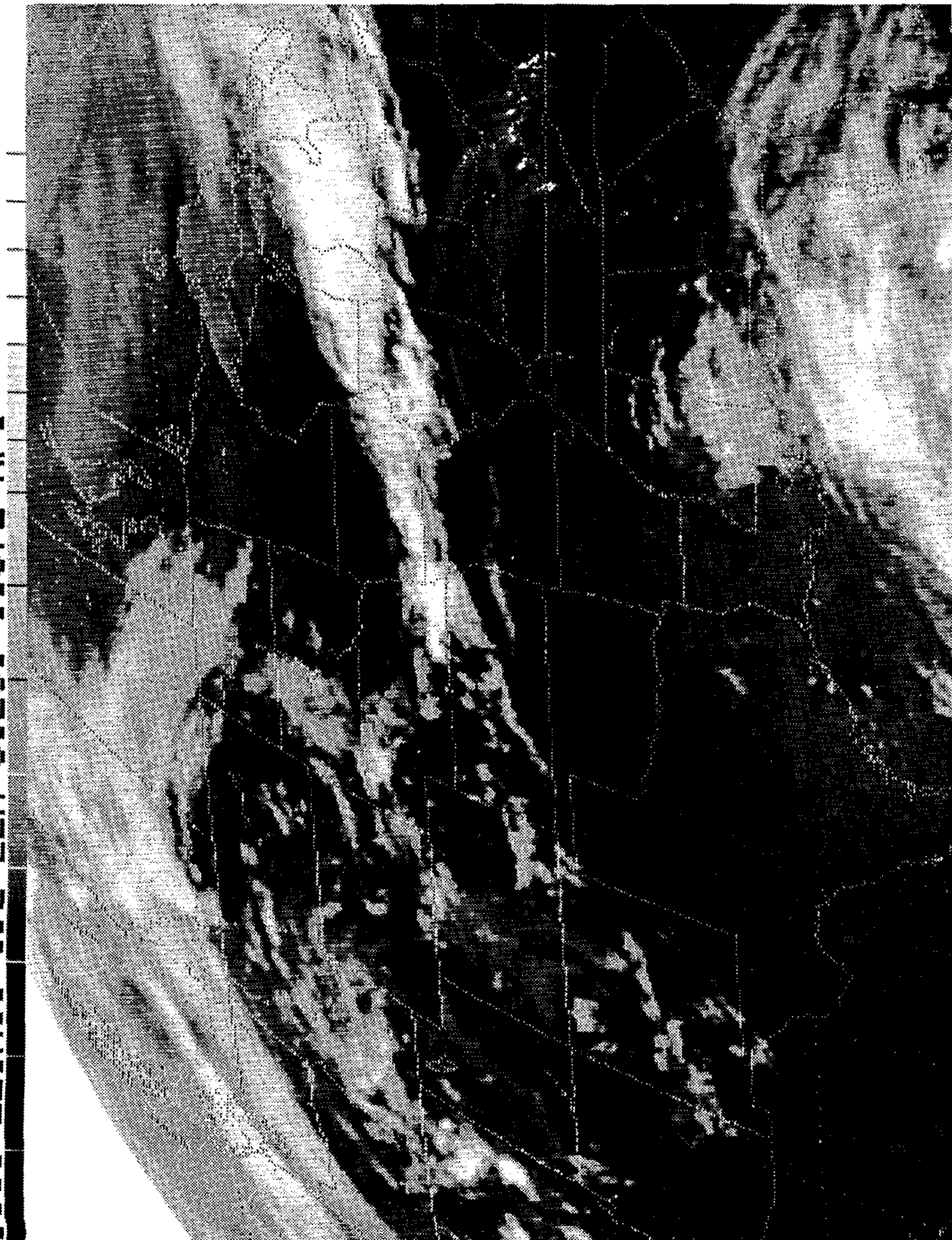



Figure 4.

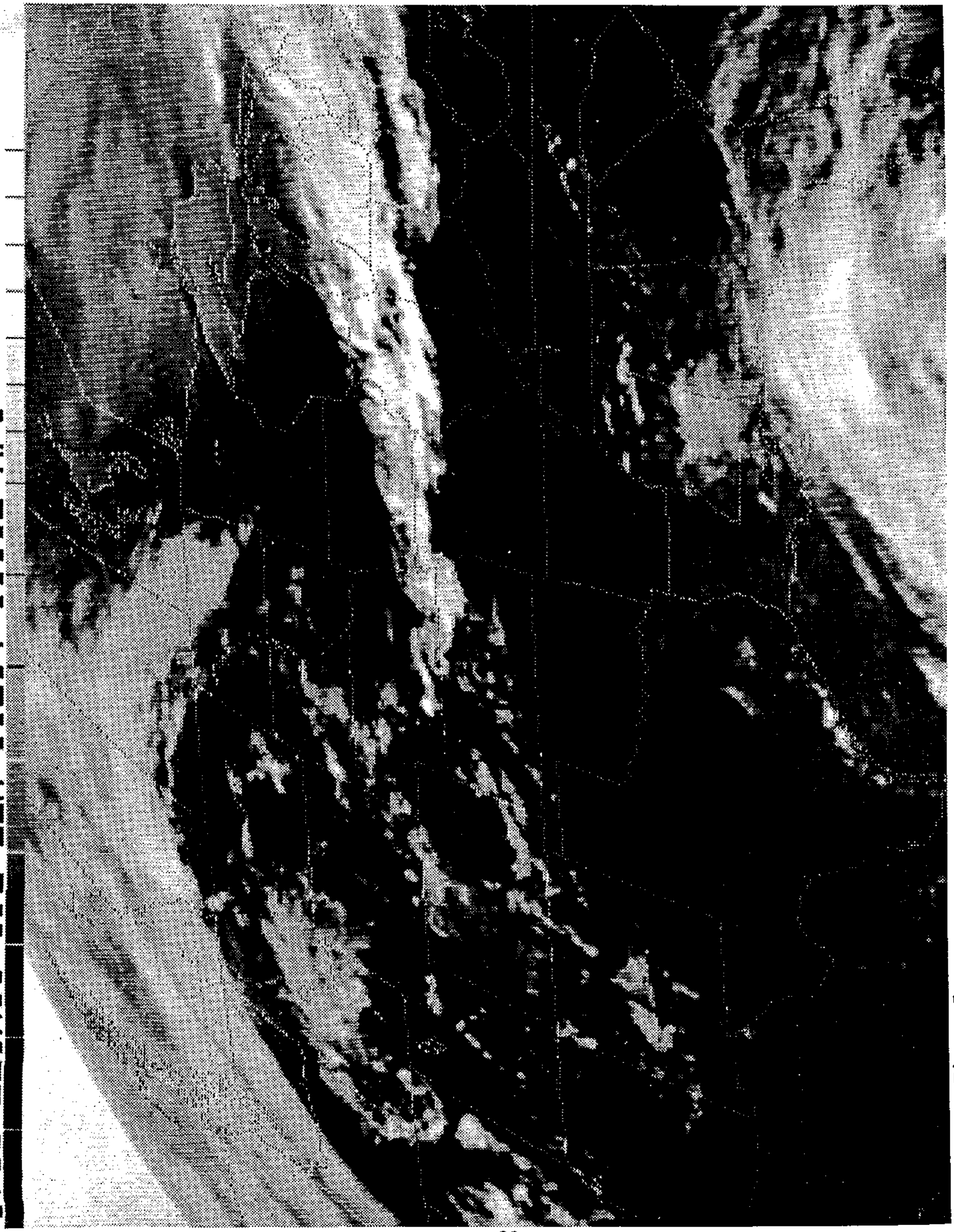



Figure 5.

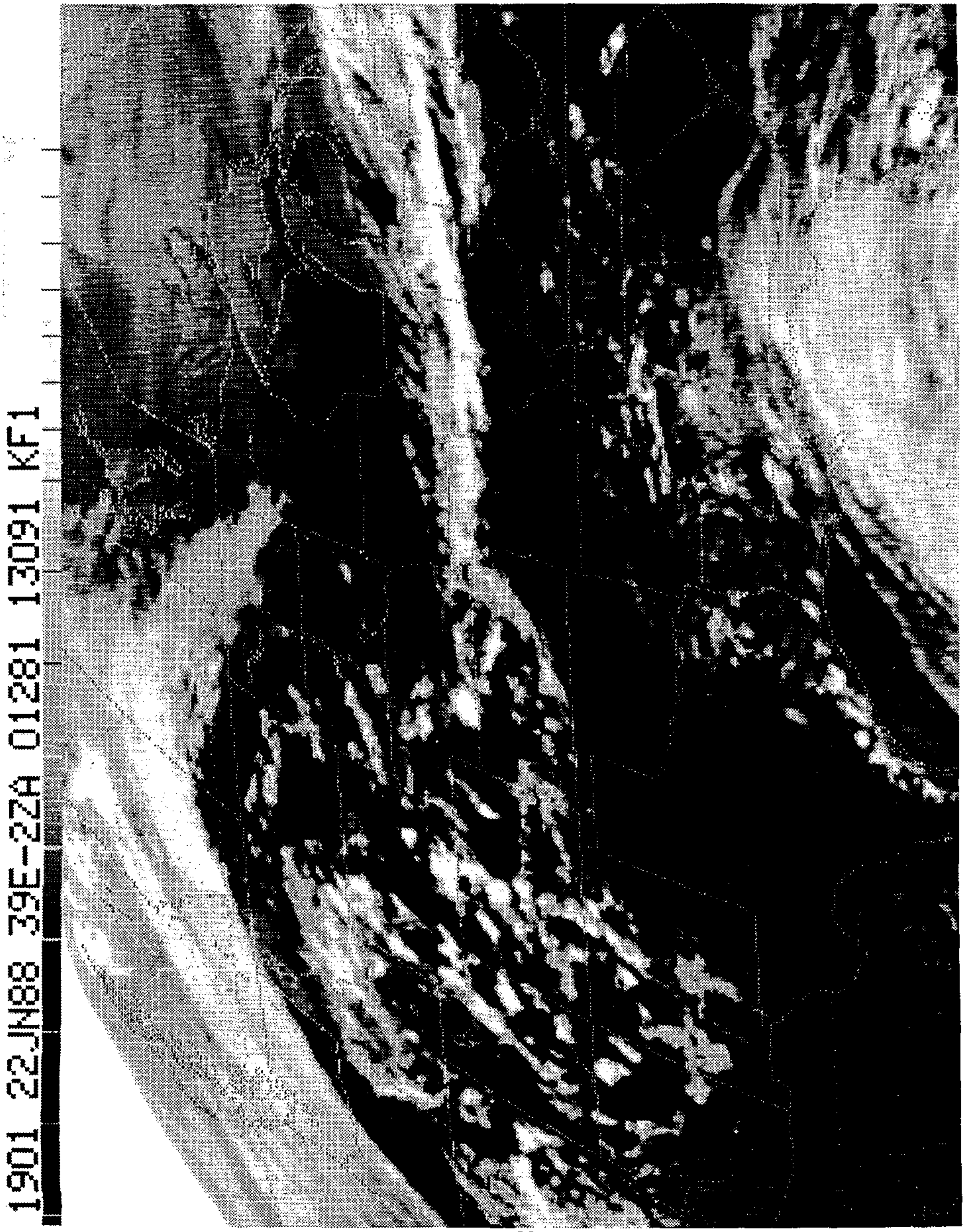



Figure 6.

Fig. 7

Reprinted from Monthly Weather Review,
vol. 93, No. 5, May 1965,pp. 278,
"The prediction of Surges in the
Southern Basin of Lake Michigan,
Part I", by G. W. Platzman

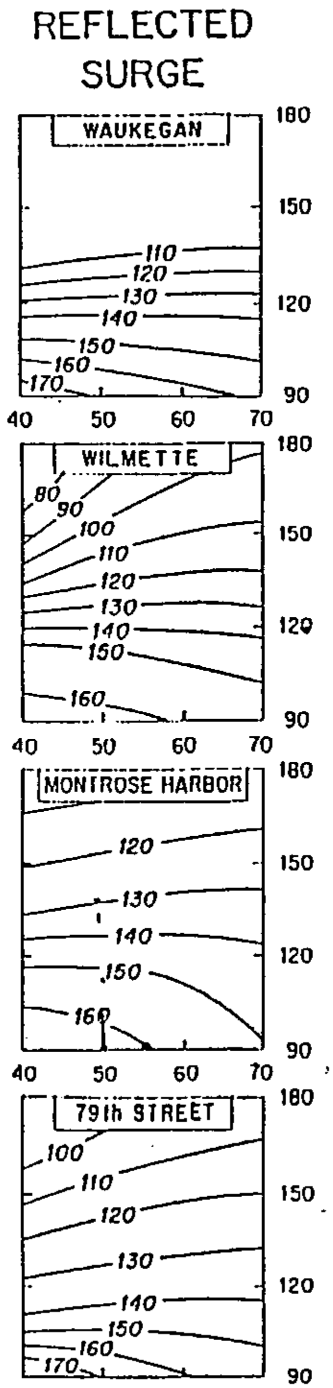



Fig. 7 A

Time in minutes between arrival of pressure jump at O'Hare and arrival of surge for four locations.

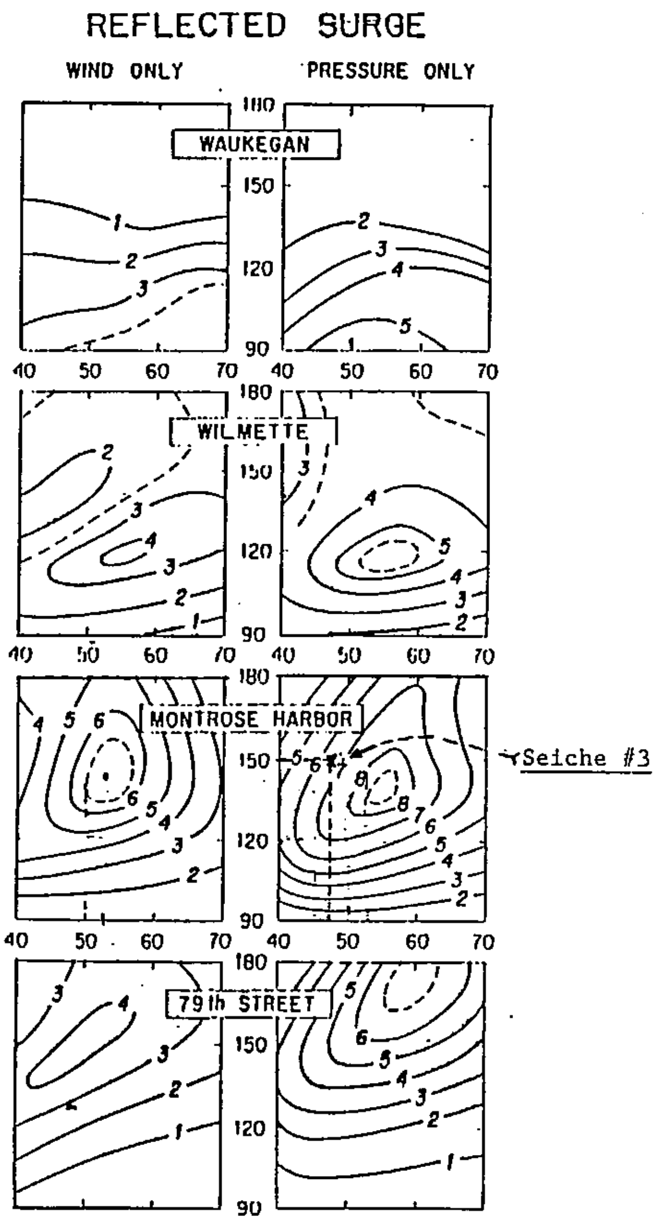



Fig. 7 B

* x-axis: speed of squall line in knots
y-axis: direction from which line is moving

Contours show factor to be used in determining amplitude of surge at four locations.

Table 1

Seiche I June 22, 1988

Reported around 1:45 p.m. CDT, not sure of time of occurrence.

Water level drops of one to three feet.

Surface Reports

| | |
|---|---|
| Madison, WI: | Altimeter +.03 in. Thunder began 5:30 a.m. CDT. Peak wind 38 knots at 5:38 a.m. CDT. |
| Milwaukee: | Altimeter +.05 in. Thunder began 8:34 a.m. CDT. |
| Rockford, IL: | Altimeter +.05 in. No thunder. |
| O'Hare: | Altimeter +.03 in. (9:30 a.m.). No thunder. |

Movement: Radar observations indicate movement from 320 degrees at 20-25 knots.

Timing:

1. See Fig. 7A for Platzman graph.

   For Montrose Harbor obtain 140-150 minutes from pressure rise at O'Hare, but probably slower since graph for >40 kt movement.

   Seiche at approximately 12:30 p.m.

2. Using satellite imagery: (see Figs. 4 through 6) Line had moved to tip of southern Lake Michigan by noon. Seiche about 1 1/2 hours later.

   Seiche at approximately 1:30 p.m.

Magnitude:

Using: average pressure rise of .04 in. factor of 3 from Fig. 7B

$$7.5 \times .04 \times 3 = .9 \text{ feet}$$

Conclusions: Timing using the Platzman graphs was too fast, because the graph is for faster moving squall lines. The magnitude underestimated drops at Calumet Harbor, but as indicated earlier, this situation favored larger fluctuations at southern harbors.

example, the critical speed is less than 40 knots, and the best direction from due North. For Wilmette and Waukegan, closer to the Illinois-Wisconsin state line, a significant seiche is produced by a line moving from the west at higher speeds.)

The second seiche of the summer occurred on July 15. It resulted in a lowering of about three to 3 1/2 feet of water with a slow gradual rise of feet at both Calumet Beach and North Shore. The observations came from the Chicago Park District. Coast Guard personnel at Wilmette and Calumet reported three to four foot fluctuations, with levels lowering two to three feet in less than 10 minutes at Calumet!

At about 9:00 a.m. CDT satellite indicated a large thunderstorm complex over the east half of Wisconsin into Upper Michigan, Lake Superior, and Lake Michigan (Fig. 8). An hour later the storms had sagged southeastward, and by 10:30 a.m. the strongest storms had moved to just south of Muskegon, Michigan on the east shore of the Lake (Figs. 9 and 10). Movement was generally from 300 degrees at about 30-40 knots.

Using Platzmans' formula, a factor of 4 was obtained from the graphs using the above direction and speed, and an average pressure rise of .06 inches was noted. The resulting water level rise was calculated as follows (Table 2):

$$7.5 \times .06 \times 4.5 = 2'$$

This value was less than observed, although it gives the forecaster a "ballpark figure" to work with. The seiche should have occurred about 2 1/2 to three hours after Milwaukee had thunder, or approximately 11:00 a.m. Since the thunderstorm was moving at only 30-35 knots, it would have been slower than indicated on Platzman's table, and indeed the level disturbances were reported around noon to 12:30 p.m. (It is interesting to note that this thunderstorm complex was so large that it also affected water levels in Lake Superior earlier that same day. The Soo Locks at Saulte Ste. Marie, Michigan reported a five foot rise in water level in 1 1/2 hours, with a subsequent four foot drop.)

The final seiche of any consequence that was reported during the summer of 1988 was on August 15th. In terms of critical values, this was the most favorable scenario of the three. However, satellite pictures revealed a much smaller thunderstorm system than those that produced the previous two seiches. Reports of three foot water level changes were reported from no less than six different harbors along the Chicago lake shore, via the Coast Guard and Chicago Park District.

At 3:00 a.m. satellite imagery displayed two thunderstorm cells developing in south central Wisconsin back to the northwest toward La Crosse (Fig. 11). The cells were developing in a train echo pattern, with the entire line shifting eastward. Thunderstorms moved across the Chicago area at 6:00 a.m., and by 9:00 a.m. the cells had moved rapidly southeastward to northeastern Indiana (Figs. 12 and 13). Movement of the storms was from

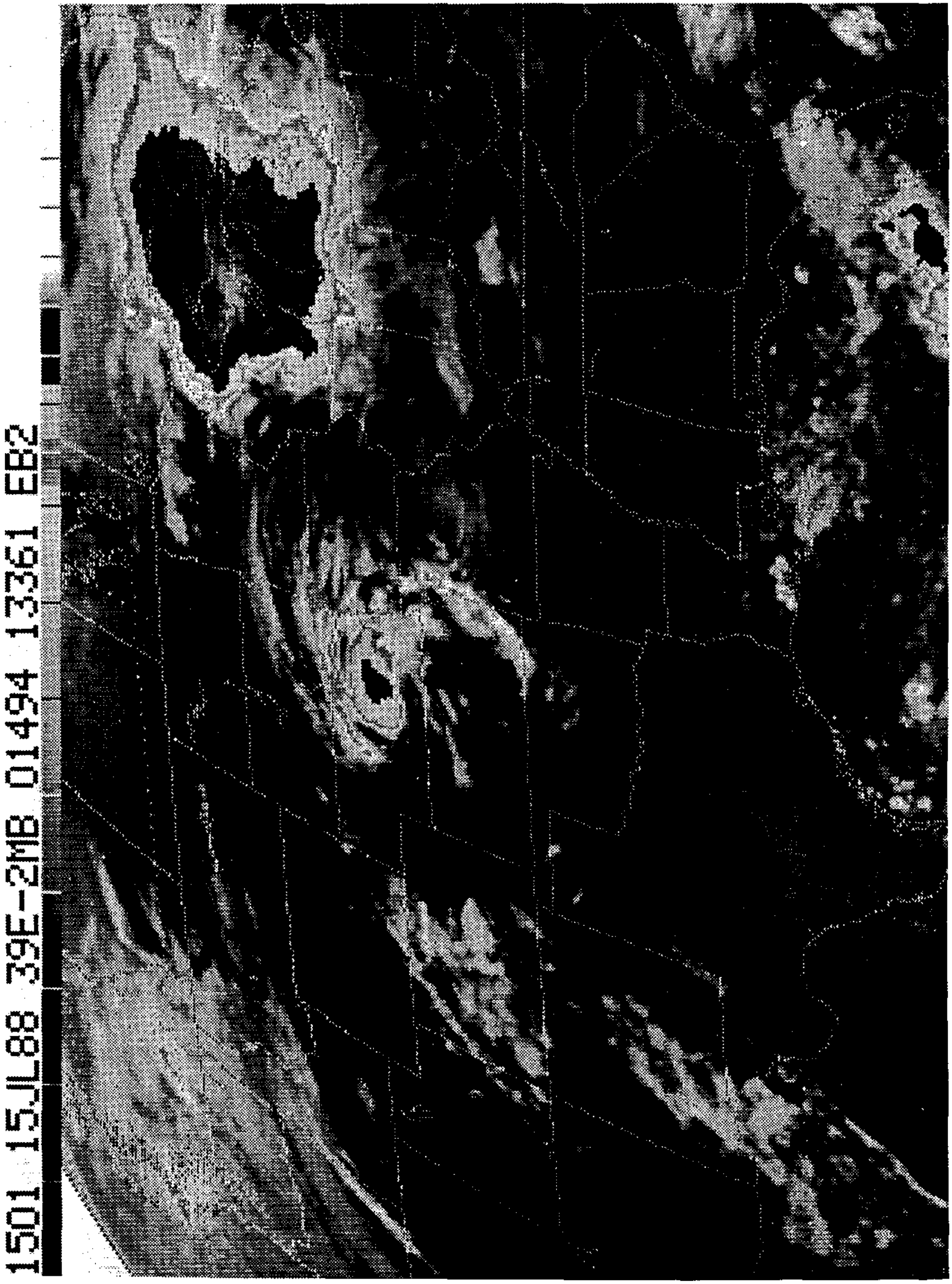



Figure 8.


Figure 9.

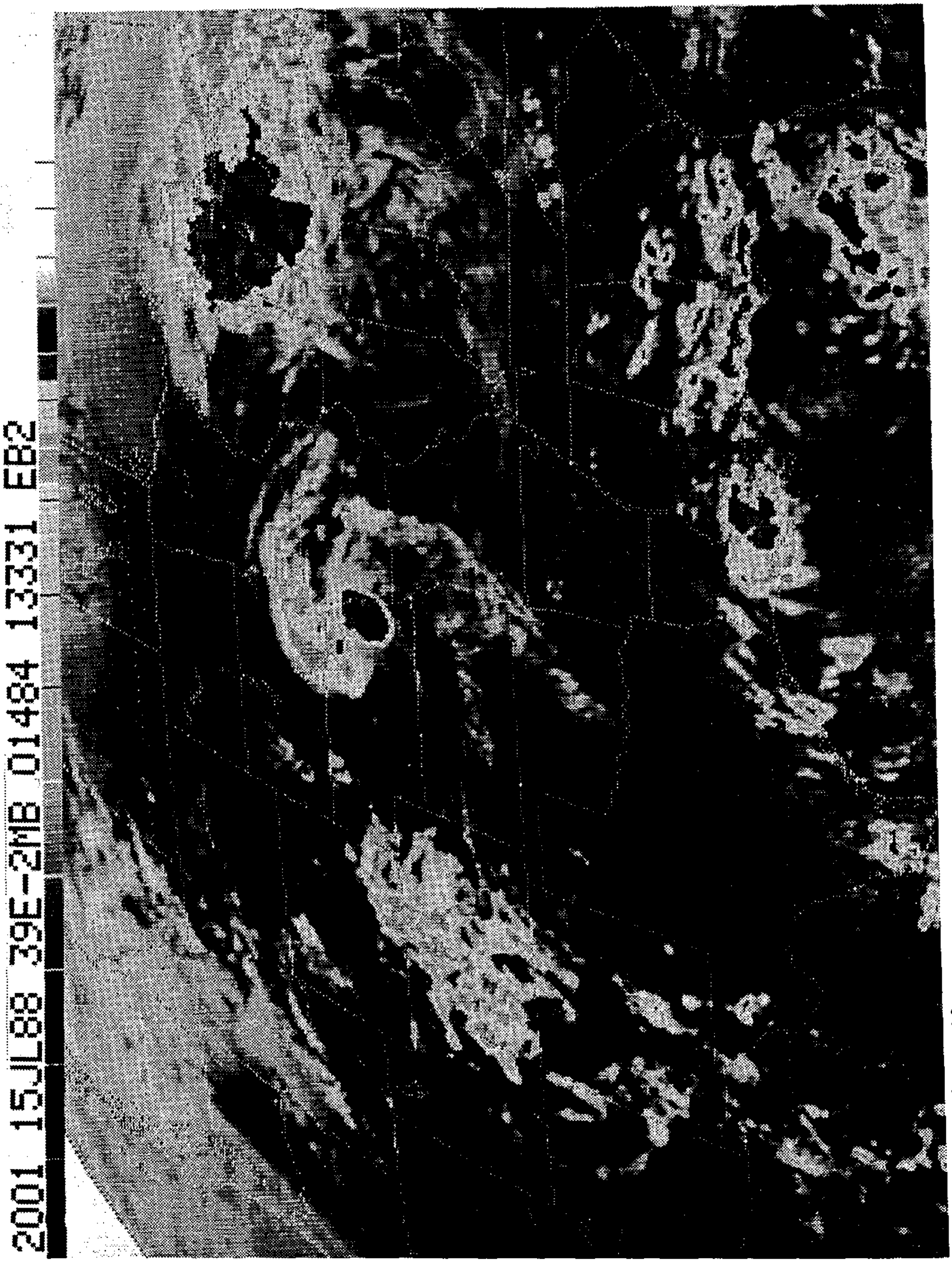



Figure 10.

Table 2

Seiche II  July 15, 1988

Reported between 12:30 p.m. and 3:00 p.m. CDT., not sure of time of occurrence.

Water level drops of three to 3 1/2 feet North Shore and Calumet Beach.

Water level drops of two to four feet at Wilmette and Calumet Harbors (at Calumet, drop was two to three feet in less than 10 minutes).

Surface Reports

| | | |
|---|---|---|
| Madison, WI: | Altimeter +.02 in. | Lightning north at 9:00 a.m. CDT. |
| Milwaukee: | Altimeter +.06 in. | Wind shift 9:00 a.m. CDT Presrr |
| Rockford, IL: | Altimeter +.05 in. | No thunder (pres rise 10a-11a) |
| O'Hare: | Altimeter little change | |

Movement: Radar observations indicate movement from 300 degrees at 30 knots.

Timing: 1. See Fig. 7A for Platzman graph.

For Montrose Harbor obtain 110-120 minutes from pressure rise at O'Hare, or about 180 minutes from rise at Rockford, (probably slower due to slower movement of storms).

Seiche at approximately 2:00-3:00 p.m.

2. Using satellite imagery not too helpful in terms of timing. Best method would have been to observe when thunderstorms hit Muskegon, Michigan or other east shore points, (around 1:00-2:00 p.m.) then add 1 1/2 hours.

Seiche at approximately 2:30-3:30 p.m.

Magnitude:

Using: average pressure rise of .06 in. factor of 5 from Fig. 7B

7.5 x .06 x 5 = 2.25 feet

Conclusions: Timing using the Platzman graphs was not reliable because the graph is for faster moving squall lines. The magnitude underestimated water level drops, but not by much. This was not a classic squall line situation at any rate, as indicated by the satellite pictures (Figs. 8 through 10) showing a large mesoscale convective complex.

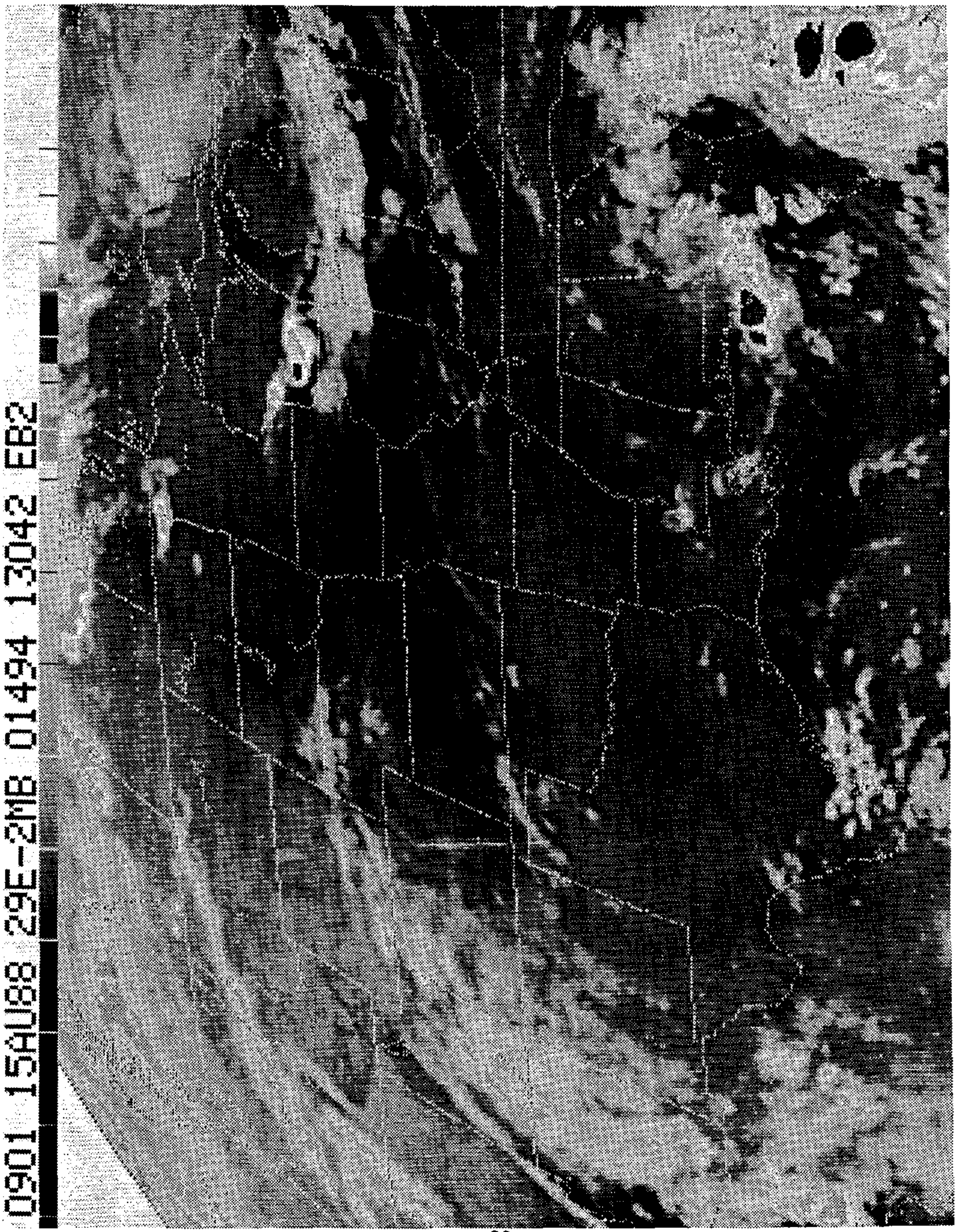



Figure 11

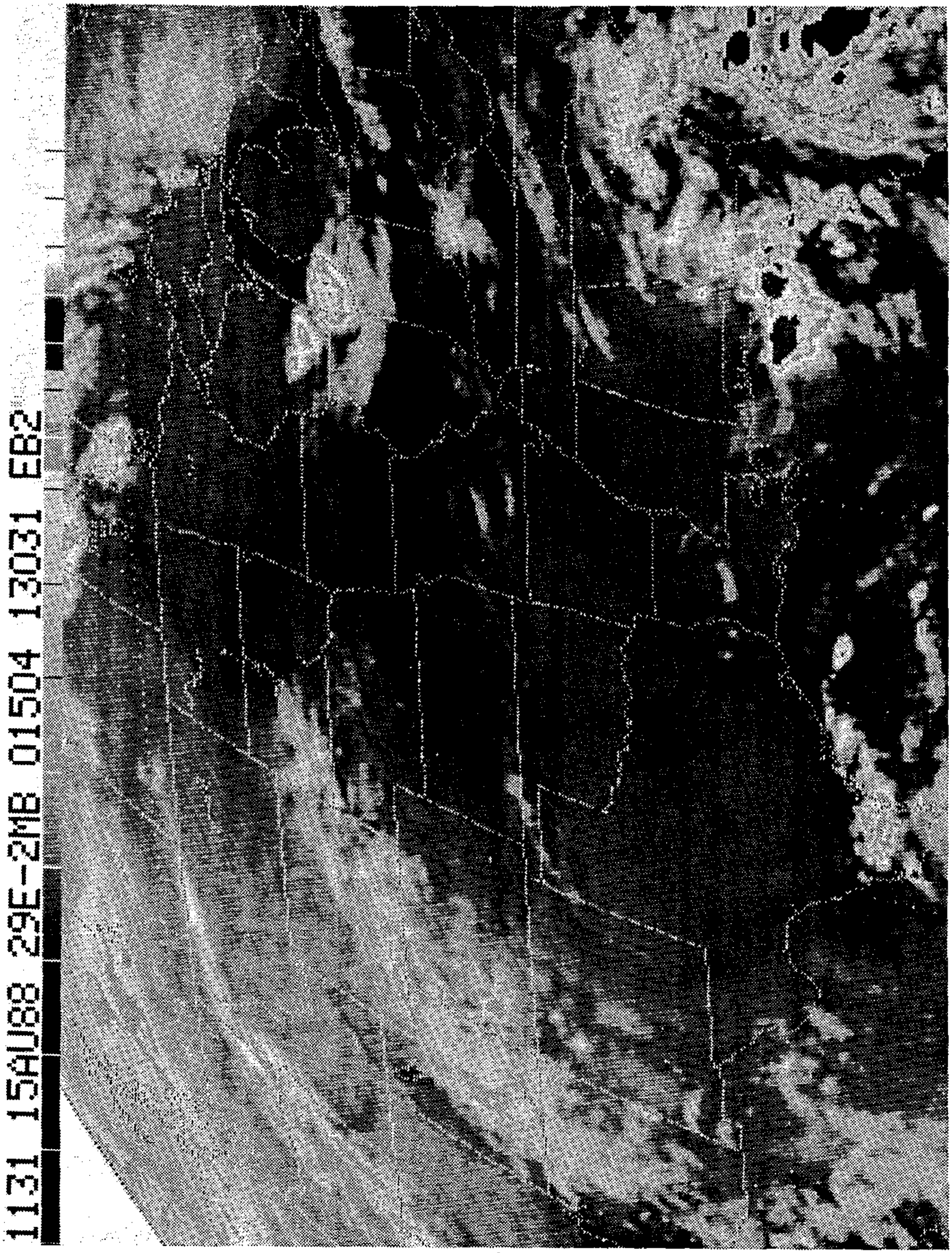



Figure 12.

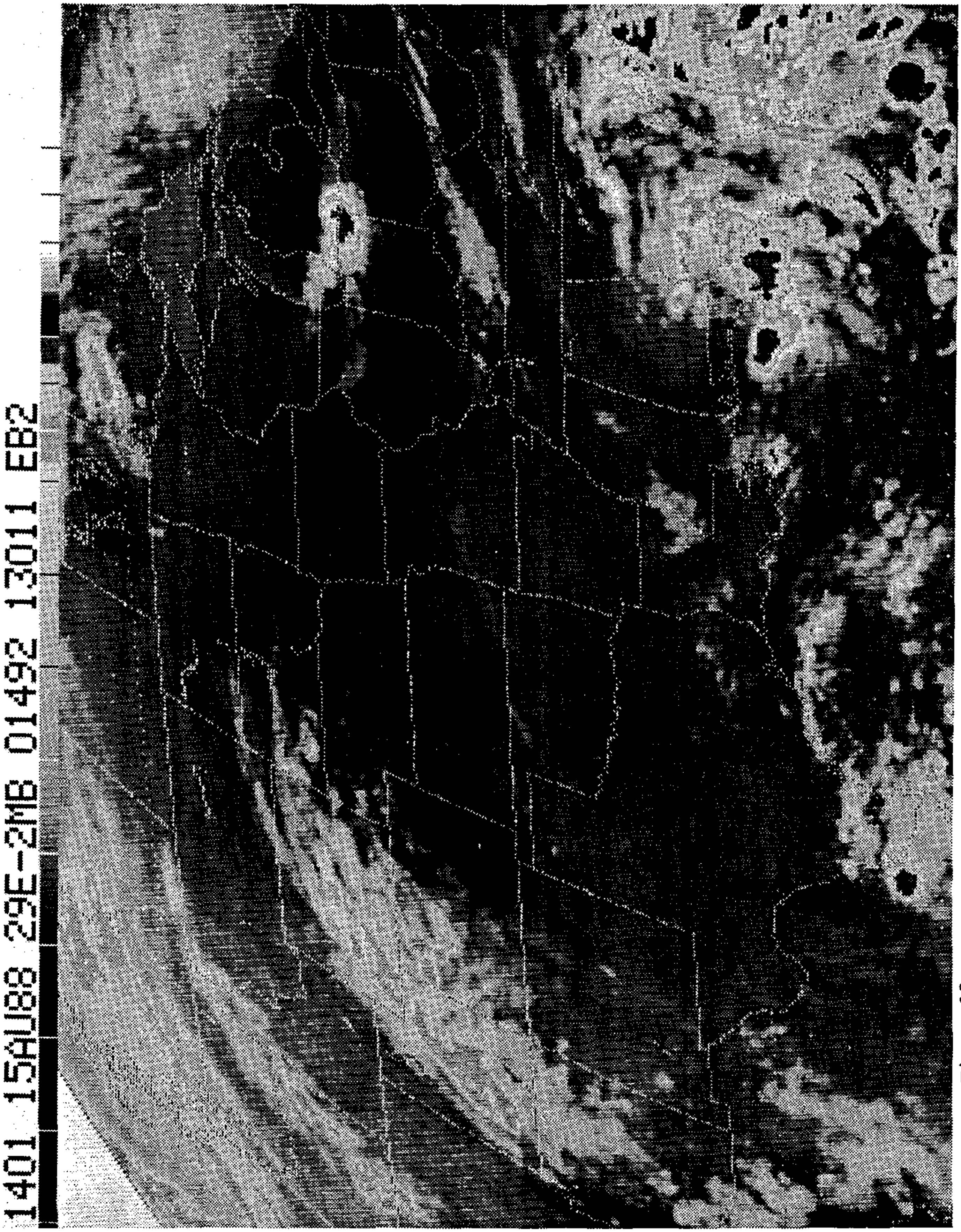



Figure 13.

300 degrees at 45-50 knots, with tops as high as 48,000 feet. (Note that the direction/speed values approach "prime" conditions.) The surge would have been calculated as follows (Table 3):

$$7.5 \times .08 \times 7 = 4.2 \text{ feet}$$

The timing of the seiche would have been about 1 1/2 to 2 1/2 hours after the thunderstorms hit Midway at 6:35 a.m., or around 8:00-9:00 a.m. Using the Platzman graphs, a time of 8:45 a.m. was calculated, and, in fact, the seiche was reported around 8:30 a.m. to 9:00 a.m. In this last event, the Platzman formulas worked out quite well with respect to magnitude of the seiche and to timing.

## 3. Summary

Seiches probably occur with more frequency than once suspected. Satellite and radar have become important tools for the forecaster with respect to the development of a seiche. The actual magnitude of the water fluctuation is still difficult to delineate, due to the influence of actors such as "reflectivity" of the east shore of the basin and slope of the lake bottom as the reflected wave moves toward the west shore.

It is obvious from the data presented in this paper that thunderstorms moving east or southeast across Lake Michigan at the "lesser" speeds of 25-40 knots will cause seiches of the order of one to four feet. The forecaster and mariner need to be especially alert, however, to those situations when "critical" values are reached; namely when a storm is moving southeastward at 50-60 knots across lower Lake Michigan.

The episodes that were studied during the 1988 summer season fit quite well with the modeling done by Platzman in the early 1960's. Further case studies need to be supplemented with continued reporting of observed water level fluctuations with an effort at pinpointing time of occurrence as well as magnitude. The reports received from the Coast Guard and the Chicago Parks District by the National Weather Service in the past have been invaluable.

## 4. Acknowledgements

I would like to thank the staff at the WSFO in Chicago for insights into specific episodes, and for relating their experiences with past seiche events. Thanks to Steve Kahn (Lead Forecaster, WSFO Chicago) for valuable input and suggestions, and to Bob Collins (PMO, WSFO Chicago) for encouraging reporting of observations from the Chicago Park District and from the U.S. Coast Guard.

## 5. References

Fulks, J. R., 1960: WSFO Chicago, Illinois Press Release, August 4, 1960. Available from WSFO Chicago, Illinois.

Table 3

Seiche III August 15, 1988

Reported around 9:00 a.m., not sure of time of occurrence as obs reported when Coast Guard shift began.

Water level drops of two to three feet from six different harbors reaching from Diversey to Calumet (Fig. 3).

Surface Reports

Madison, WI: Thunder began 3:47 a.m.

Milwaukee: Altimeter +.08 in. (Prjmp 5:15-5:23 a.m.) Thunder began 5:01 a.m.

Rockford, IL: No sgwx

O'Hare: Altimeter +.07 in. (Prjmp 5:15-5:30 a.m.) Thunder began 6:38 a.m.

Movement: Radar observations indicate movement from 300 degrees at 45 knots.

Timing: 1. See Fig. 7A for Platzman graph.

For Montrose Harbor obtain 120 minutes from pressure rise at O'Hare.

Seiche at approximately 7:15 a.m. CDT

2. Using satellite imagery would place the thunderstorms on the east shore around 7:00 a.m.

Seiche at approximately 8:30 a.m.

Magnitude:

Using: average pressure rise of .08 in. factor of 6.5 from Fig. 7B

7.5 x .08 x 6.5 = 3.9 feet

Conclusions: Timing using the Platzman graph was probably very good. The magnitude using the same scheme was an excellent representation of what actually occurred. Since the movement and speed of this particular area of thunderstorms was very close to "classic" conditions for seiche development, the use of Platzman's technique verified very well.

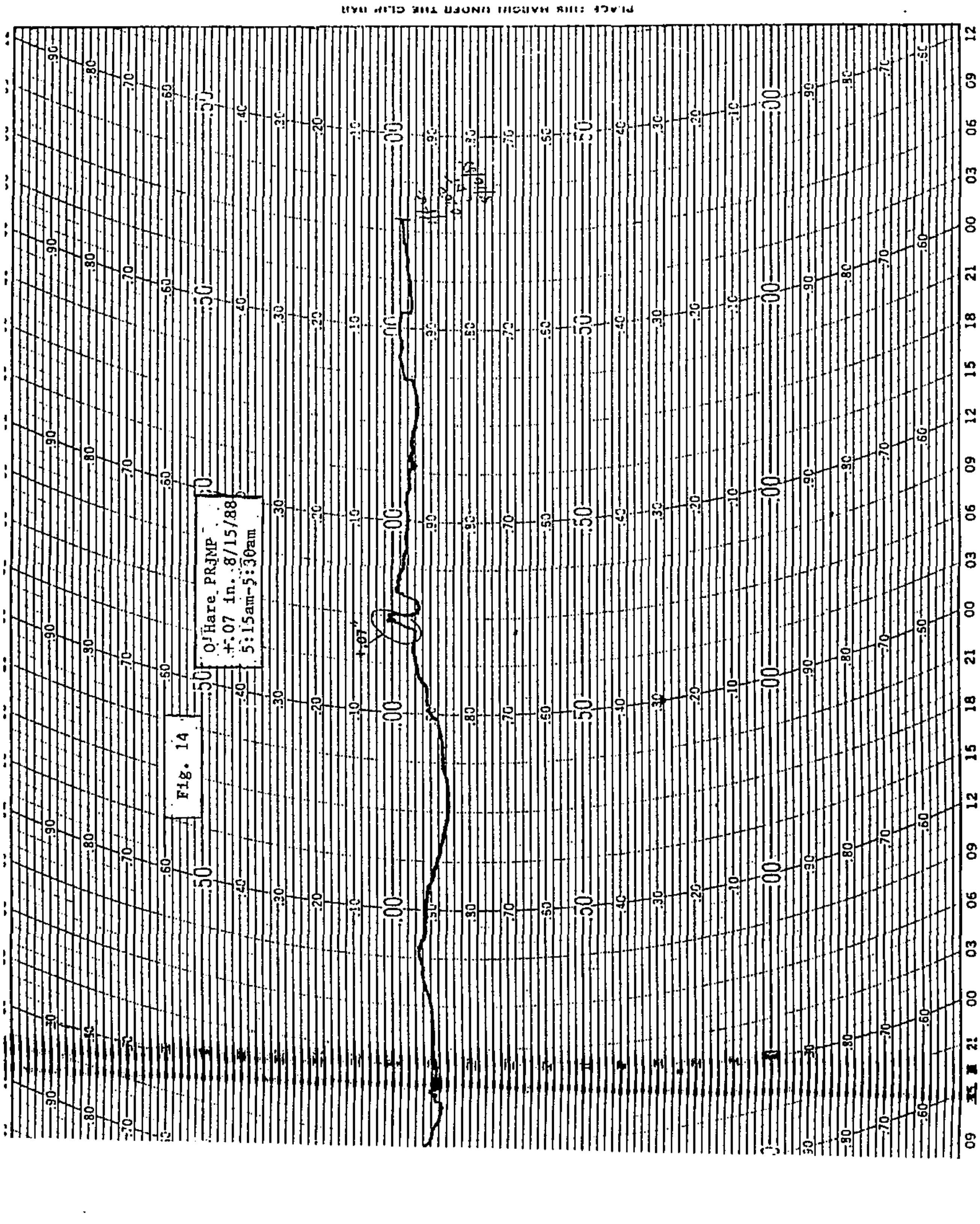



Fig. 14

Gordon, W. M., 1985: <u>The Big Wave</u>. Chicago Tribune Magazine, August 18, 1985, pp. 54-61,

Hughes, L. A., 1970: Seiche: The Quiet Killer. <u>ESSA</u>, 36-39.

Platzman, G. W., 1965: The prediction of surges in the Southern Basin of Lake Michigan, Part 1: The Dynamical basis for prediction. <u>Mon. Wea. Rev.</u>, <u>93</u>, 275-281,

NWS CR 49 A Preliminary Transport Wind and Mixing Height Climatology, St. Louis, Missouri. Donald E. Wuerch, Albert J. Courtois, Carl Ewald, Gary Ernst, June 1972 (COM 72-10859).

NWS CR 50 An Objective Forecast Technique for Colorado Downslope Winds. Wayne E. Sangster, December 1972 (COM 73-10280).

NWS CR 51 Effect on Temperature and Precipitation of Observation Site Change at Columbia, Missouri. Warren M. Wisner, March 1973 (COM 73-10734).

NWS CR 52 Cold Air Funnel Clouds. Jack R. Cooley and Marshall E. Soderberg, September 1973, (COM 73-11753/AS).

NWS CR 53 The Frequency of Potentially Unfavorable Temperature Conditions in St. Louis, Missouri. Warren M. Wisner, October 1973.

NWS CR 54 Objective Probabilities of Severe Thunderstorms Using Predictors from FOUS and Observed Surface Data. Clarence A. David, May 1974 (COM 74-11258/AS).

NWS CR 55 Detecting and Predicting Severe Thunderstorms Using Radar and Sferics. John V. Graff and Duane C. O'Malley, June 1974 (COM 74-11335/AS).

NWS CR 56 The Prediction of Daily Drying Rates. Jerry D. Hill, November 1974 (COM 74-11806/AS).

NWS CR 57 Summer Radar Echo Distribution Around Limon, Colorado. Thomas D. Karr and Ronald L. Wooten, November 1974 (COM 75-10076/AS).

NWS CR 58 Guidelines for Flash Flood and Small Tributary Flood Prediction. Lawrence A. Hughes and Lawrence L. Longsdorf, October 1975 (PB247569/AS)

NWS CR 58 (Revised) March 1978 (PB281461/AS)

NWS CR 59 Hourly Cumulative Totals of Rainfall - Black Hills Flash Flood June 9-10, 1972. Don K. Halligan and Lawrence L. Longsdorf, April 1976 (PB256087).

NWS CR 60 Meteorological Effects on the Drift of Chemical Sprays. Jerry D. Hill, July 1976 (PB259593).

NWS CR 61 An Updated Objective Forecast Technique for Colorado Downslope Winds. Wayne E. Sangster, March 1977 (PB266966/AS).

NWS CR 62 Design Weather Conditions for Prescribed Burning. Ronald E. Haug, April 1977 (PB268034).

NWS CR 63 A Program of Chart Analysis (With Some Diagnostic and Forecast Implications). Lawrence A. Hughes, December 1977 (PB279866/AS).

NWS CR 64 Warm Season Nocturnal Quantitative Precipitation Forecasting for Eastern Kansas Using the Surface Geostrophic Wind Chart. Wayne E. Sangster, April 1979 (PB295982/AS).

NWS CR 65 The Utilization of Long Term Temperature Data in the Description of Forecast Temperatures. Arno Perlow, November 1981 (PB82 163064).

NWS CR 66 The Effect of Diurnal Heating on the Movement of Cold Fronts Through Eastern Colorado. James L. Wiesmueller, August 1982 (PB83 118463).

NWS CR 67 An Explanation of the Standard Hydrologic Exchange Format (SHEF) and Its Implementation in the Central Region. Geoffrey M. Bonnin and Robert S. Cox, April 1983 (PB83 193623).

NWS CR 68 The Posting of SHEF Data to the RFC Gateway Database. Geoffrey M. Bonnin, April 1983 (PB83 222554).

NWS CR 69 Some Basic Elements of Thunderstorm Forecasting. Richard P. McNulty, May 1983 (PB83 222604).

NWS CR 70 Automatic Distribution of AFOS Products Created at the NOAA Central Computer Facility via Hamlet (RJE) Punch Stream. Billy G. Olsen and Dale G. Lillie, November 1983 (PB84 122605).

NWS CR 71 An Investigation of Summertime Convection Over the Upper Current River Valley of Southeast Missouri. Bartlett C. Hagemeyer, July 1984 (PB84 222389).

NWS CR 72 The Standard SHEF Decoder Version 1.1. Geoffrey M. Bonnin, August 1984 (PB85 106508).

NWS CR 73 The Blizzard of February 4-5, 1984 Over the Eastern Dakotas and Western Minnesota. Michael Weiland, October 1984 (PB85 120087).

NWS CR 74 On the Observation and Modeling of the Slope Winds of the Upper Current River Valley of Southeast Missouri and Their Relationship to Air-Mass Thunderstorm Formation. Bartlett C. Hagemeyer, June 1985 (PB85 226926/AS).

NWS CR 75 Complete Guide to Canadian Products in AFOS. Craig Sanders, July 1985 (PB85 228153/AS).

NWS CR 76 The Reliability of the Bow Echo as an Important Severe Weather Signature. Ron W. Przybylinski and William J. Gery, September 1985 (PB86 102340).

NWS CR 77 Observation of Bow Echoes with the Marseilles Radar System. John E. Wright, Jr., September 1985 (PB86 102340).

NWS CR 78 Statistical Analysis of SHEF Coding Errors. Robert S. Cox, Jr., January 1986 (PB86 145141).

NWS CR 79 On the Midwestern Diurnal Convergence Zone on the West Side of the Warm Season Bermuda High. Bartlett C. Hagemeyer, March 1986 (PB86 171378).

NWS CR 80 Some Characteristics of Northeast Kansas Severe Weather 1963-1984. Larry W. Schultz, March 1986 (PB86 173952/AS).

NWS CR 81 The Severe Thunderstorm Outbreak of July 6, 1983 in Southeast Idaho, Western Wyoming and Southwest Montana. Gary L. Cox, April 1986 (PB86 184322/AS).

NWS CR 82 Some Proposals for Modifying the Probability of Precipitation Program of the National Weather Service. Wayne E. Sangster and Michael D. Manker, July 1986 (PB86 226636/AS).

NWS CR 83 Deformation Zones and Heavy Precipitation. Henry Steigerwaldt, August 1986 (PB86 229085/AS).

NWS CR 84 An Overview of the June 7, 1984 Iowa Tornado Outbreak. Charles H. Myers, August 1987.

NWS CR 85 Operational Detection of Hail by Radar Using Heights of VIP-5 Reflectivity Echoes. Richard B. Wagenmaker, September 1987.

NWS CR 86 Fire Weather Verification: The Forecaster Does Make a Difference. Therese Z. Pierce and Scott A. Mentzer, December 1987 (PB88 140744).

NWS CR 87 Operational Use of Water Vapor Imagery. Samuel K. Beckman, December 1987 (PB88 140751).

NWS CR 88 Central Region Applied Research Papers 88-1 Through 88-7. NWS Central Region, Scientific Services Division, May 1988 (PB88-210836).

NWS CR 89 Compendiums of Information for the Missouri Basin River Forecast Center and the North Central River Forecast Center. NWS Central Region, Scientific Services Division, June 1988 (PB88-226204).

NWS CR 90 Synoptic-Scale Regimes Most Conducive to Tornadoes in Eastern Wyoming — A Link Between the Northern Hemispheric Scale Circulation and Convective-Scale Dynamics. William T. Parker and Edward K. Berry, July 1988 (PB88-231337).

NWS CR 91 Heavy Snowfall in Northwest Wyoming. Michael S. Weiland, September 1988 (PB89 109524).

NWS CR 92 On the Utility of a Geographic Information System in Modelling Climatic Suitability. Bartlett C. Hagemeyer, September 1988 (PB89 109516).

NWS CR 93 The Synoptic and Meso-Alpha Scale Meteorology of Wyoming Flash Floods. Joseph A. Rogash, October 1988 (PB89 117709).

NWS CR 94 The Removal of Stagnant Winter Air Masses From Wyoming's Wind River Basin. Gary L. Cox and Jeffrey M. Graham, November 1988 (PB89 128664).

NWS CR 95 Floods Along Des Plaines and Fox Rivers: September-October 1986. Thomas L. Dietrich, February 1989 (PB89 152797/AS).

NWS CR 96 A Case Study Evaluation of Satellite-Derived Rainfall Estimates and Their Application to Numerical Model Precipitation Forecast Verification. Glenn A. Field, May 1989 (PB89 194591).

NWS CR 97 Central Region Applied Research Papers 97-1 through 97-6. NWS Central Region, Scientific Services Division, July 1989 (PB89 213375/AS).

NWS CR 98 The Record Rainfall of August 13-14, 1987 at Chicago, Illinois. Paul Merzlock, November 1989.